Jets in Clusters

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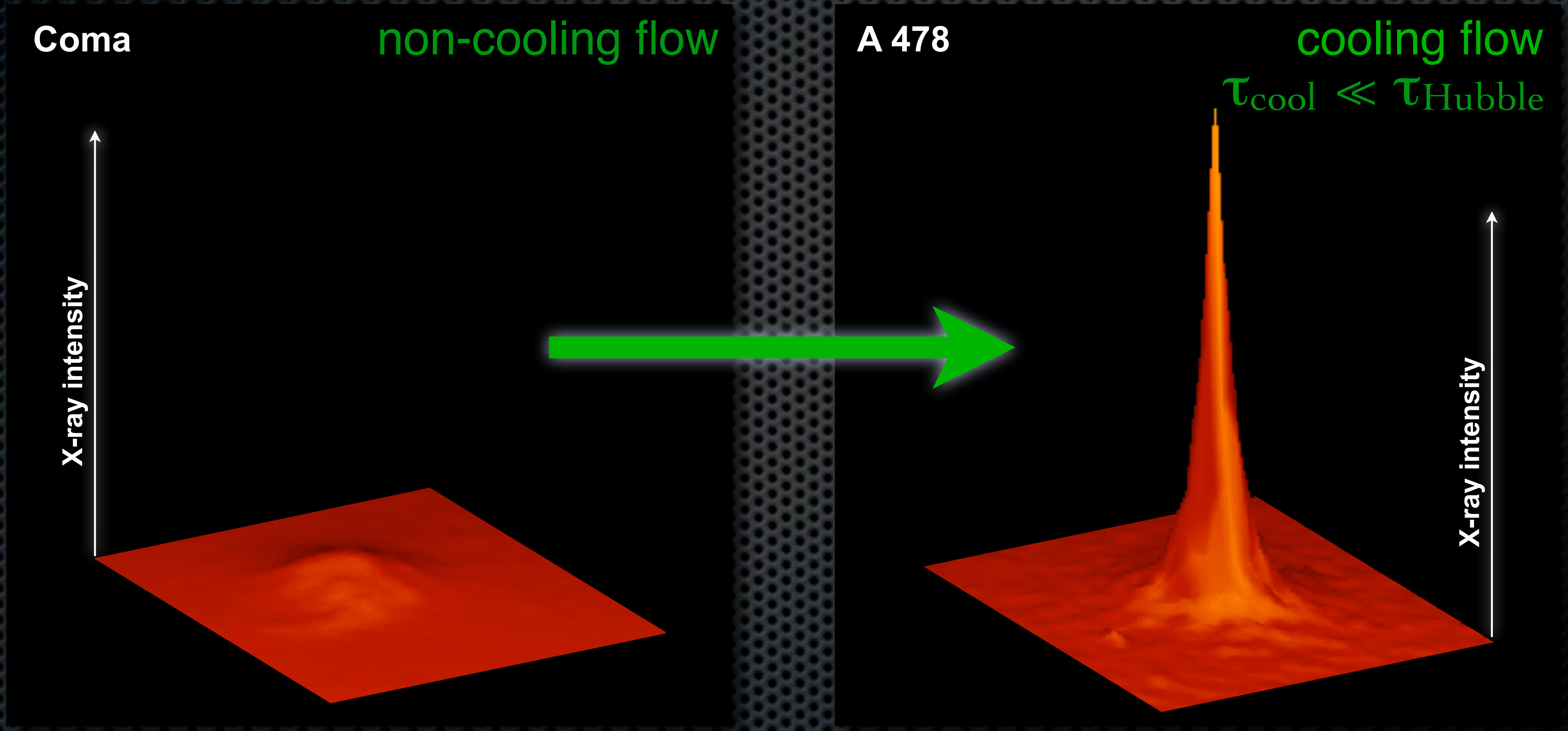
Outline

- Clusters as probes of jet physics
- Jets in dynamic clusters
  - Multiple bubbles vs. intermittency
  - Isotropy and AGN “spheres of influence”
  - Kinematic signatures of jet activity
- The fate of “fossil” radio plasma

The (no-)cooling problem



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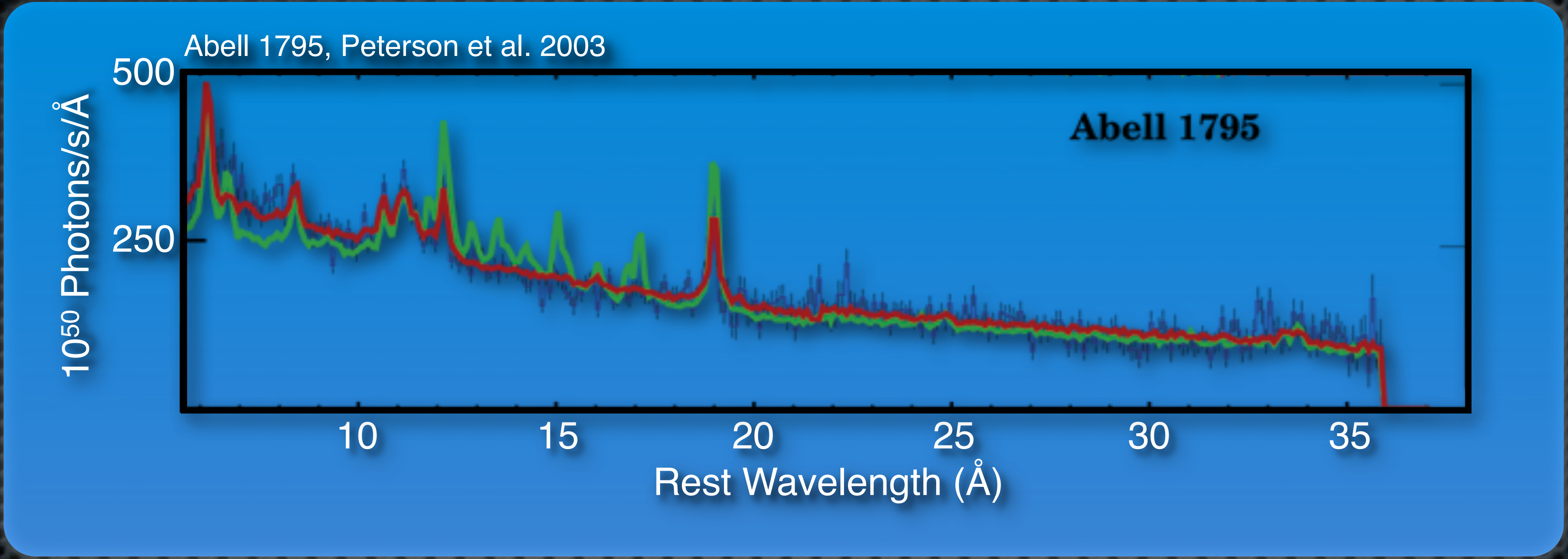

- Gas stops cooling at 1/3 Virial temperature ~ 1.5 keV

⇒ Something must counter-act the cooling

- Burns (90):
  - All cool cores have radio loud AGN in their center

Chandra's cluster legacy

- Cavities
- Sound waves
- Shocks

Perseus (Fabian et al. 2008)

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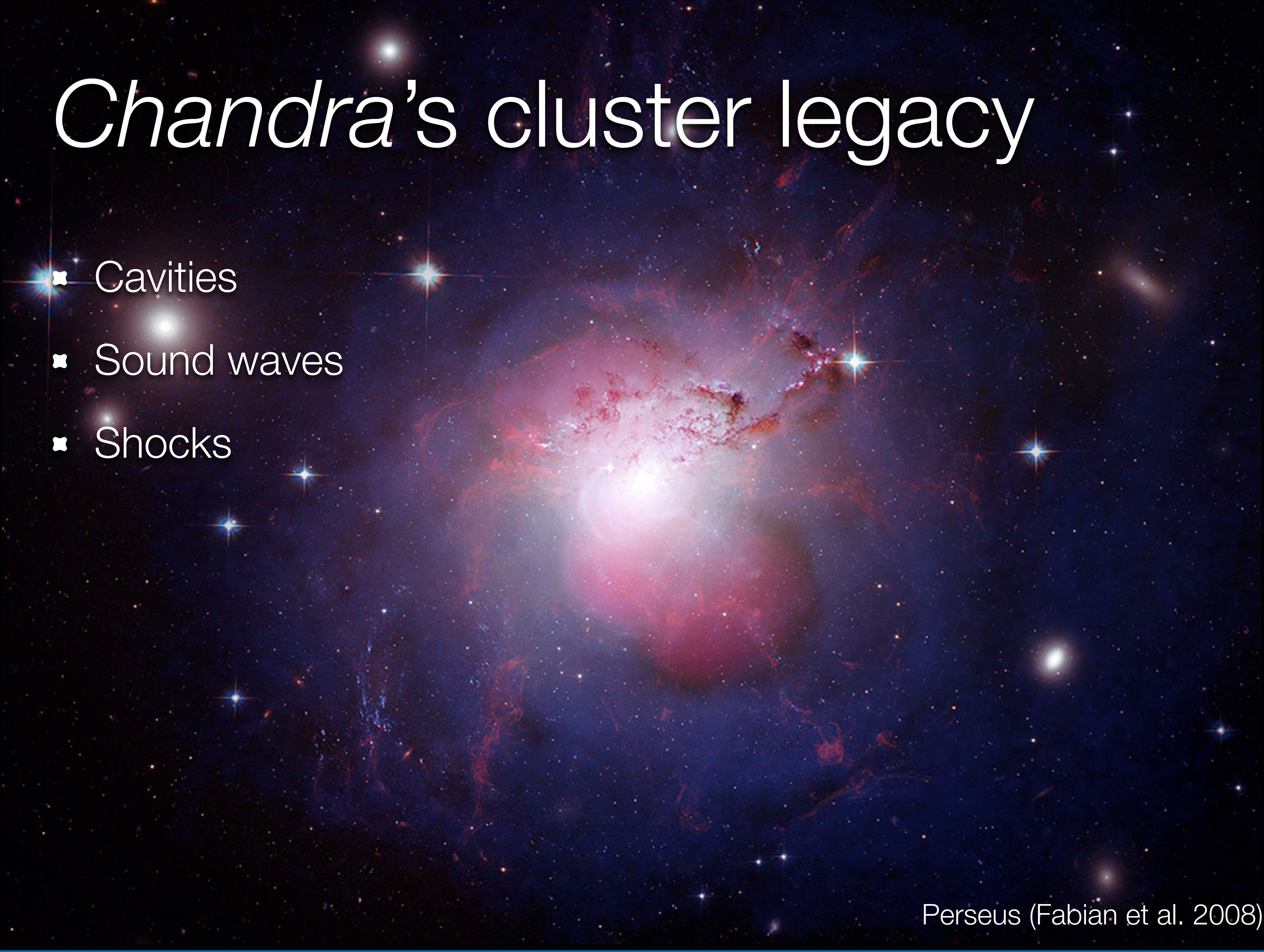
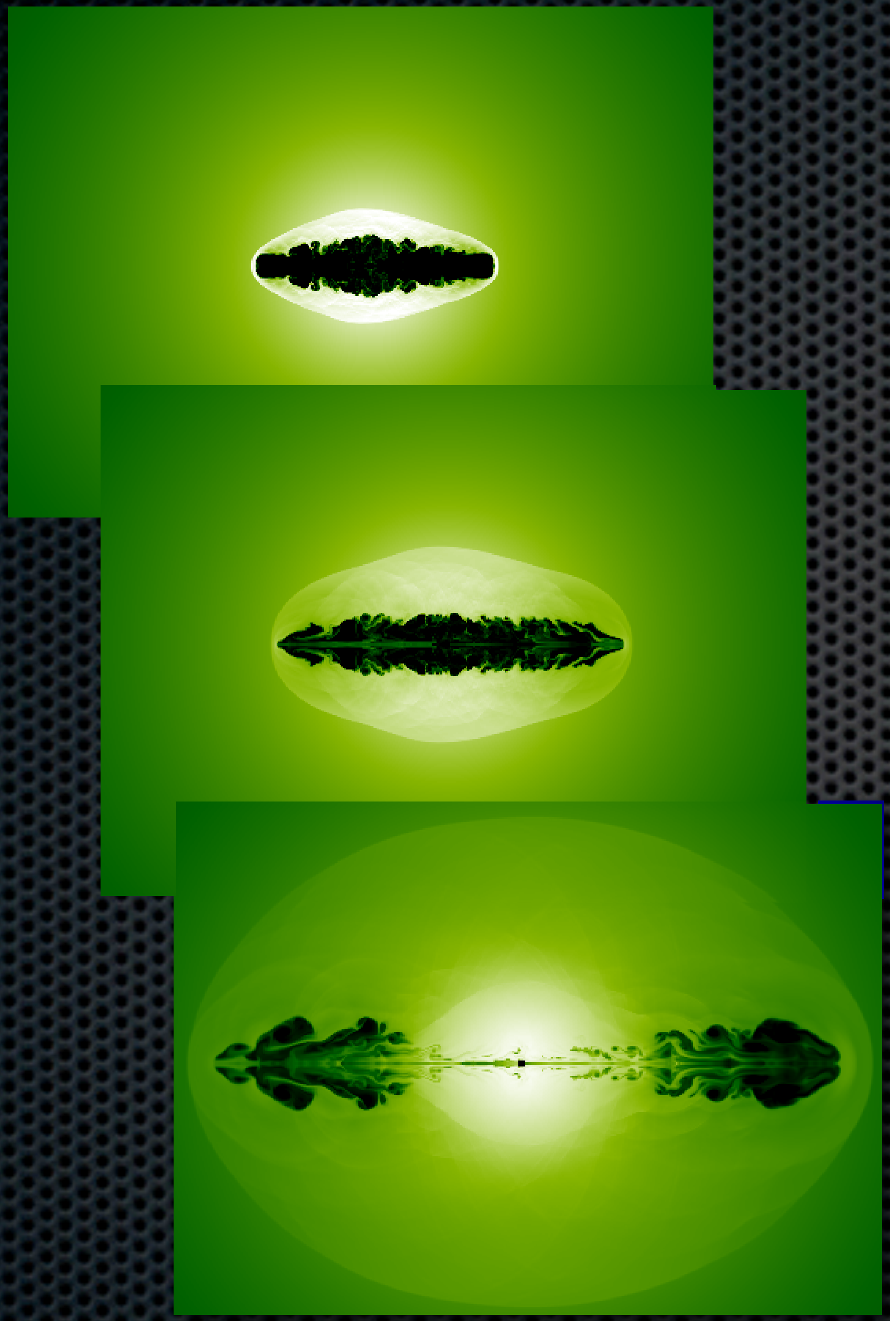


Perseus (Fabian et al. 2008)

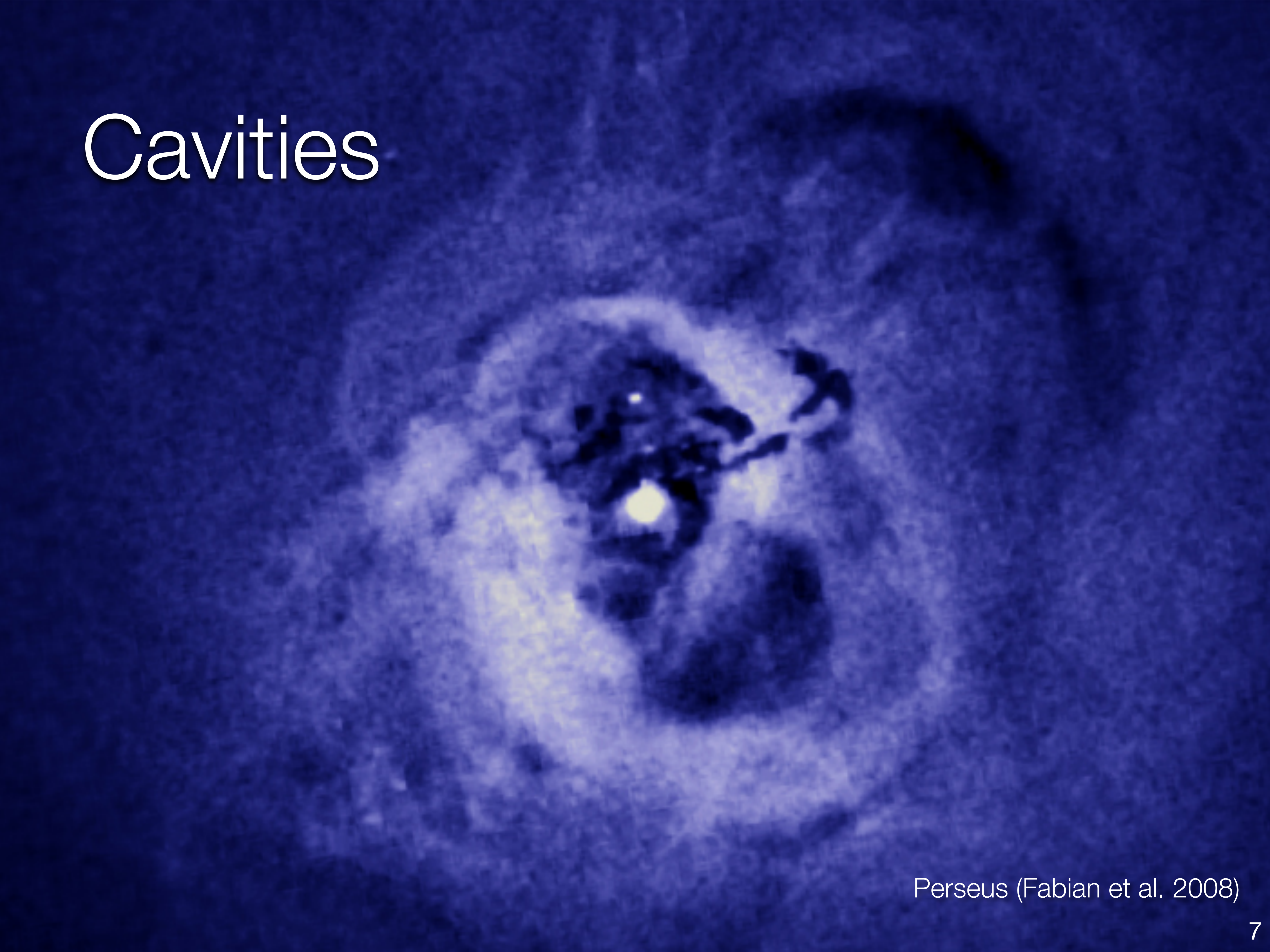
Radio source evolution



- Supersonic
- Transonic
- Buoyant (detached)

Reynolds, Heinz, & Begelman 2002

Cavities



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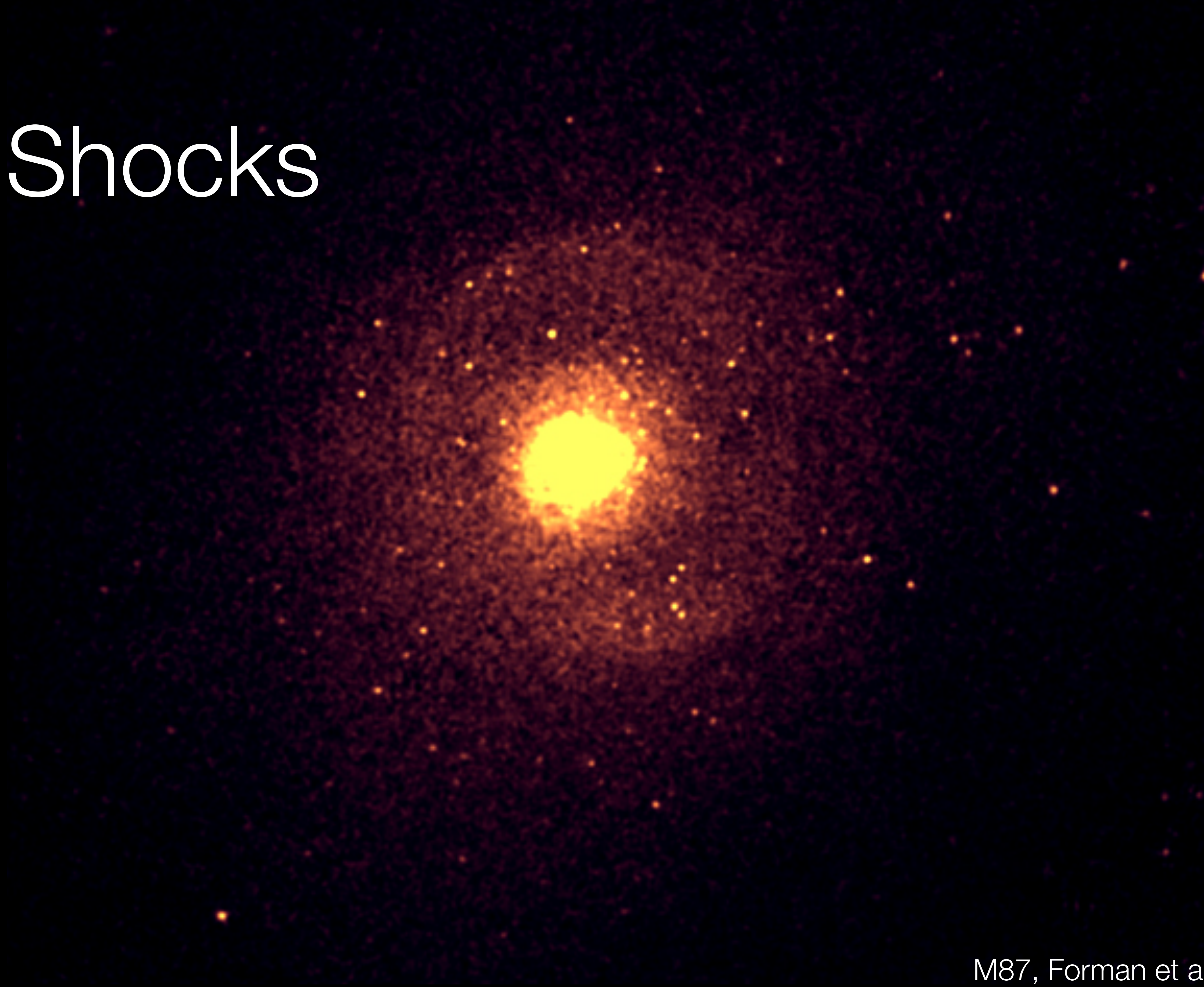
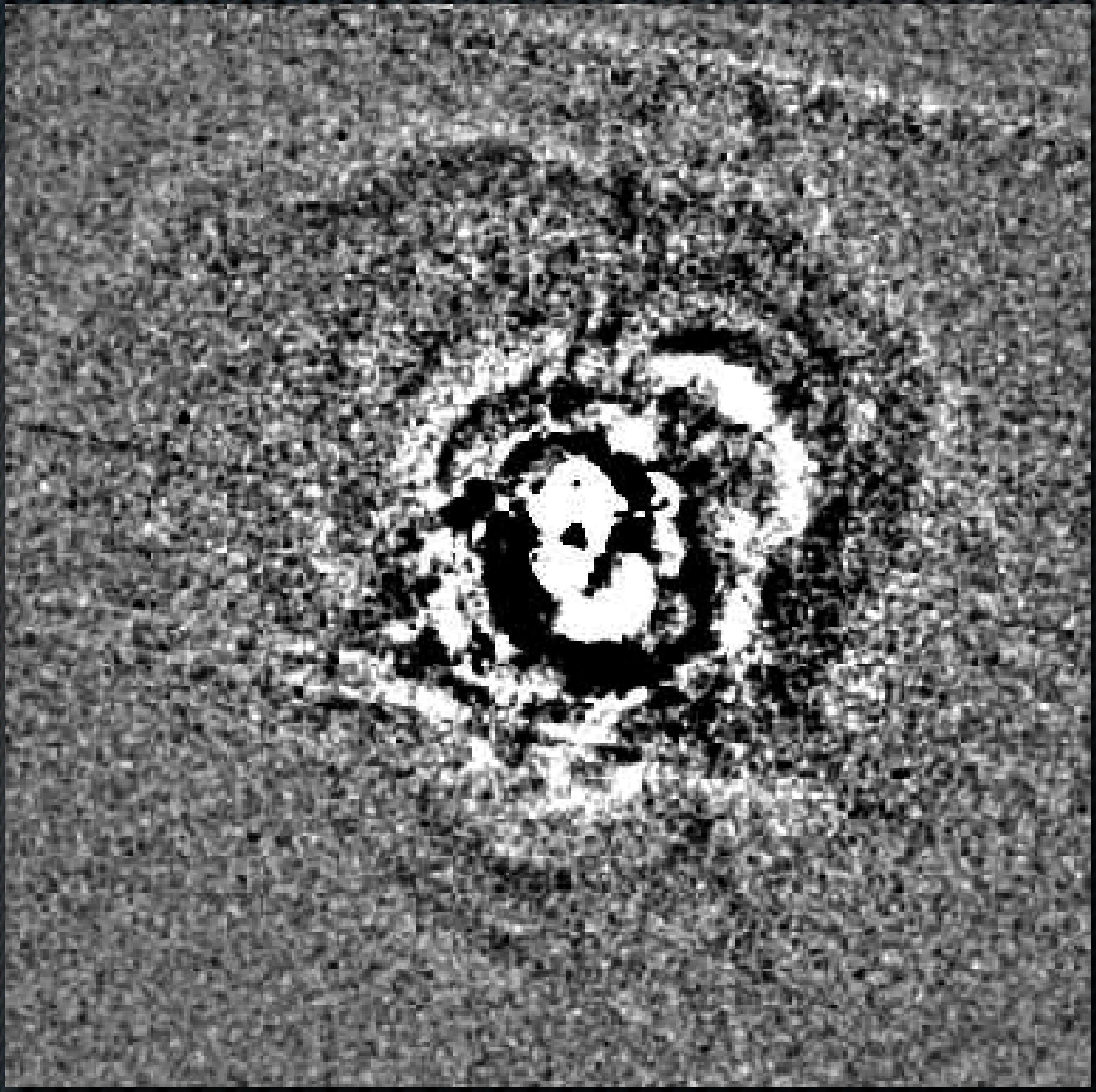
Shocks



M87, Forman et al. 2007

Sound waves



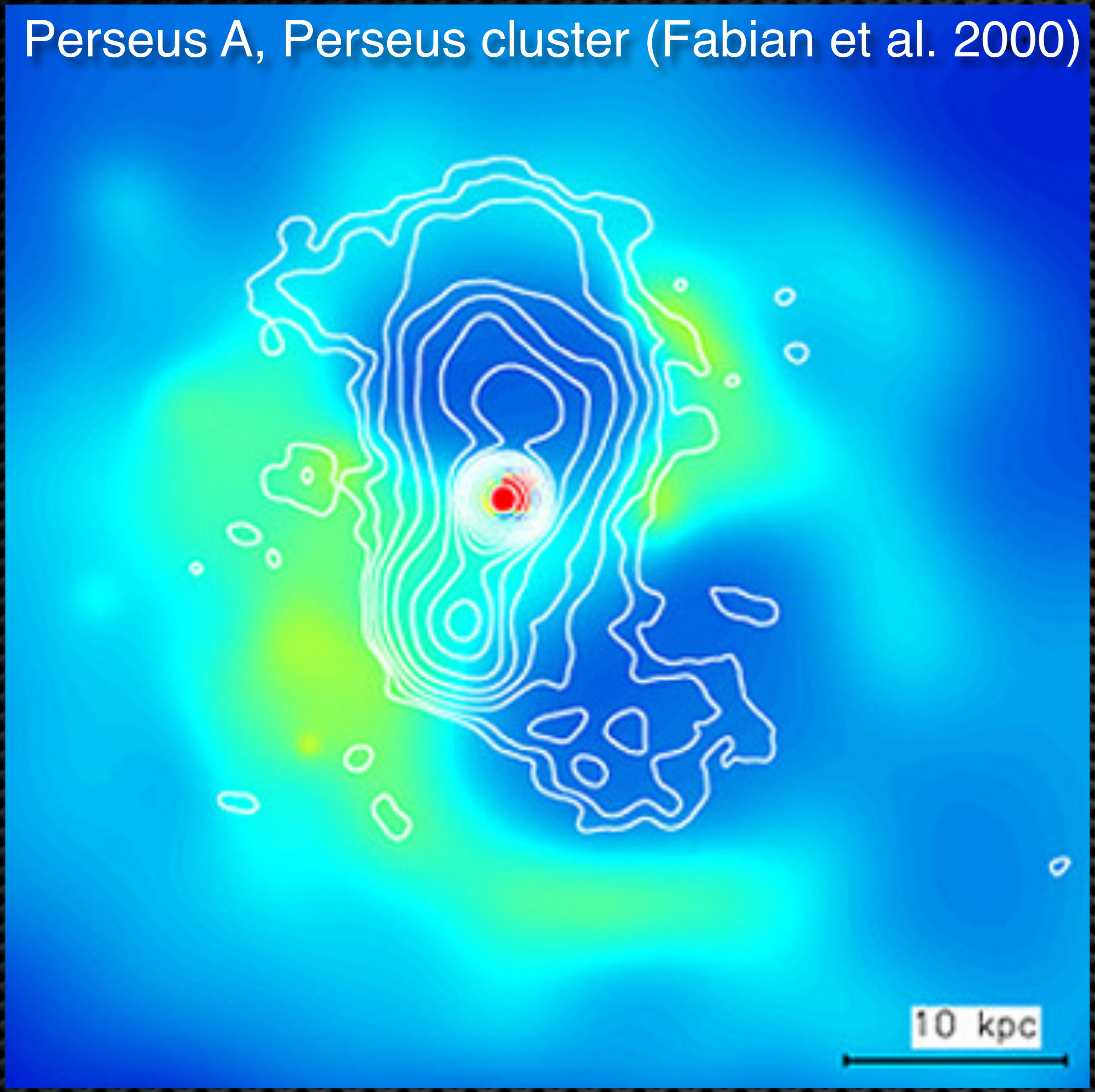
10^{-4} bpM

Perseus (Fabian et al. 2003)

Perseus

B. Cellini (1554)

Energetics



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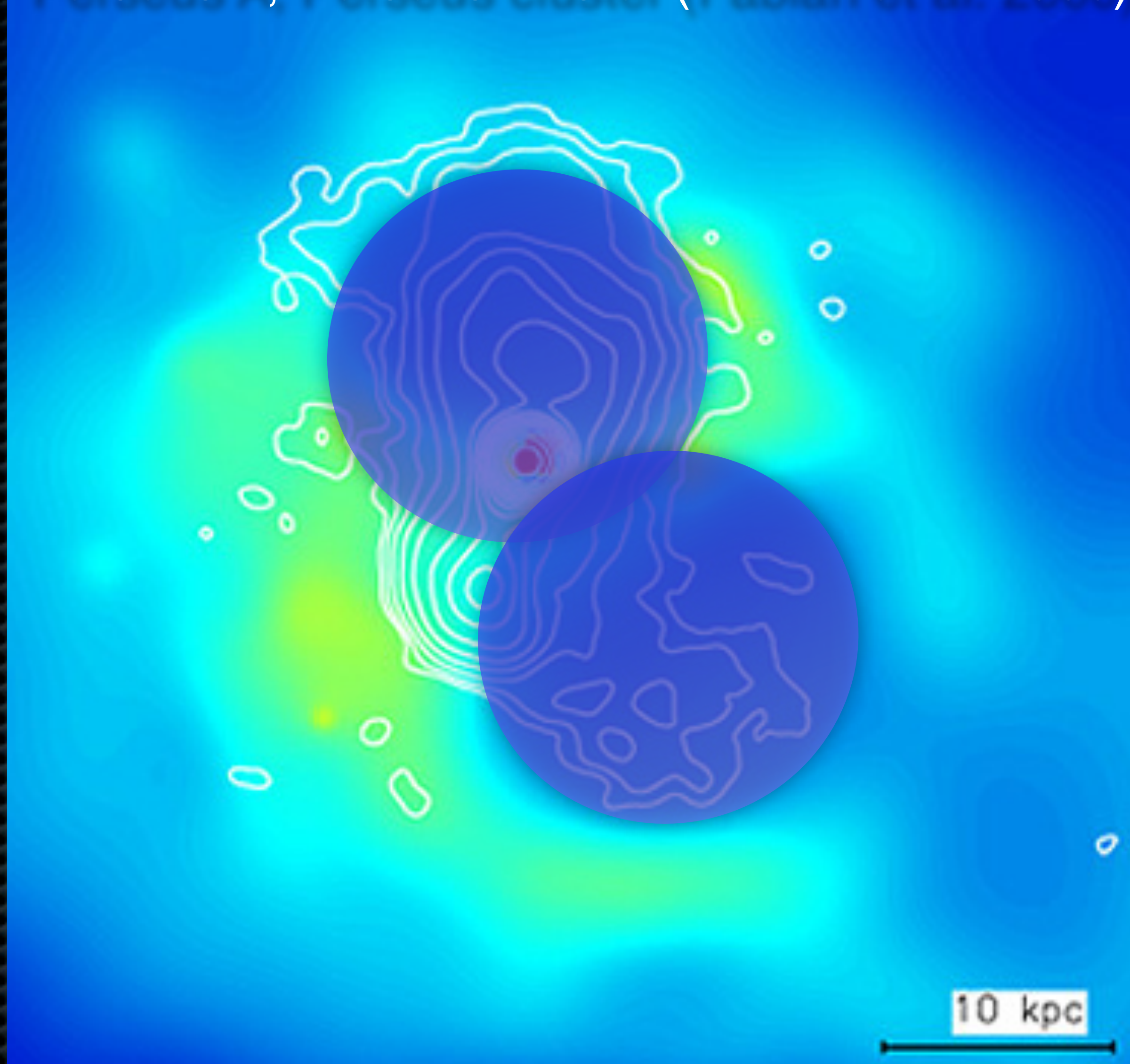


Perseus A, Perseus cluster (Fabian et al. 2000)

$$E \approx 4pV$$

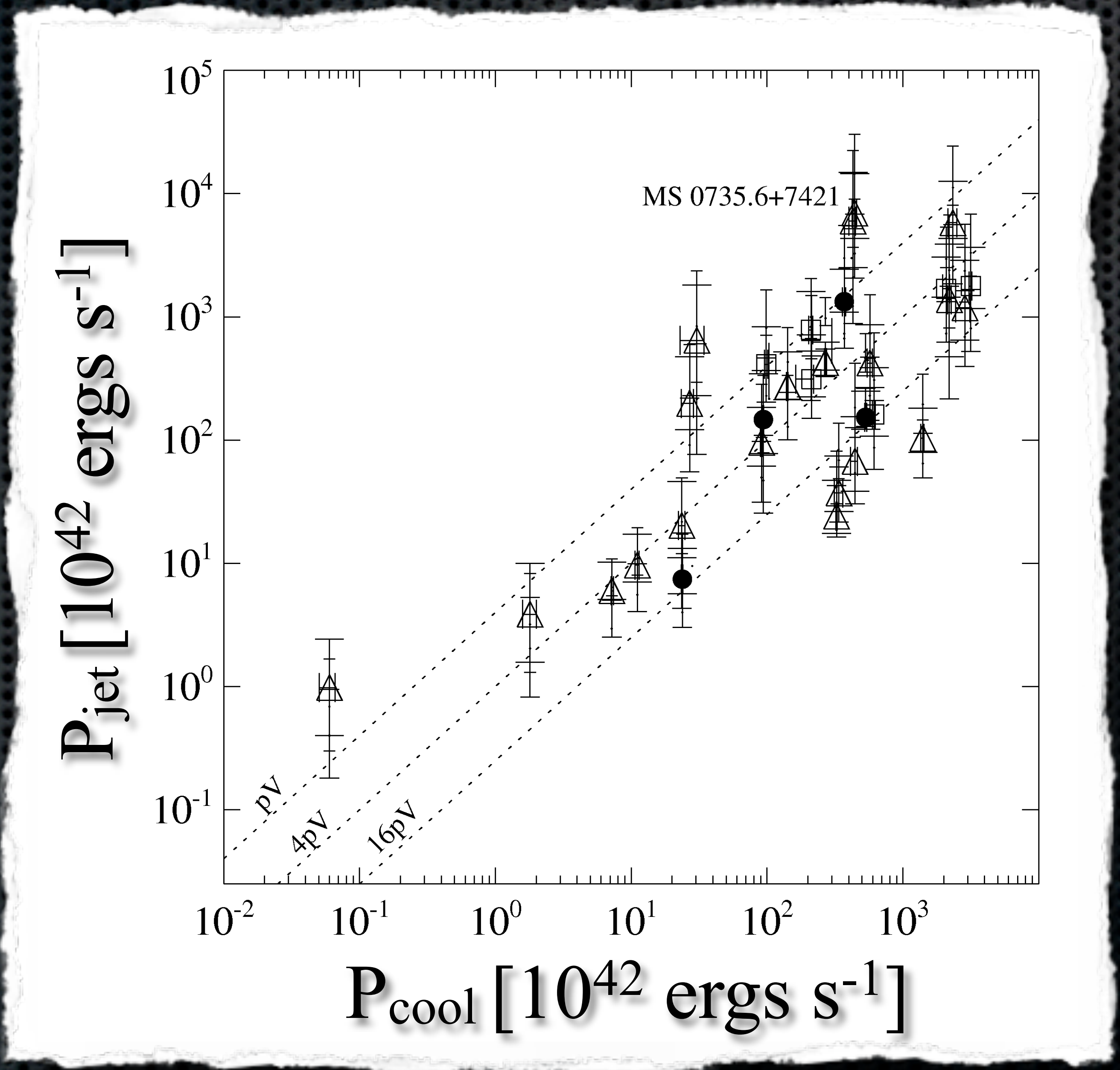
$$v_{\rm exp} \approx v_{\rm bouy}$$

$$t_{\rm age} \approx R/v_{\rm buoy}$$

$$\langle W_{\rm jet} \rangle \approx E/t_{\rm age}$$

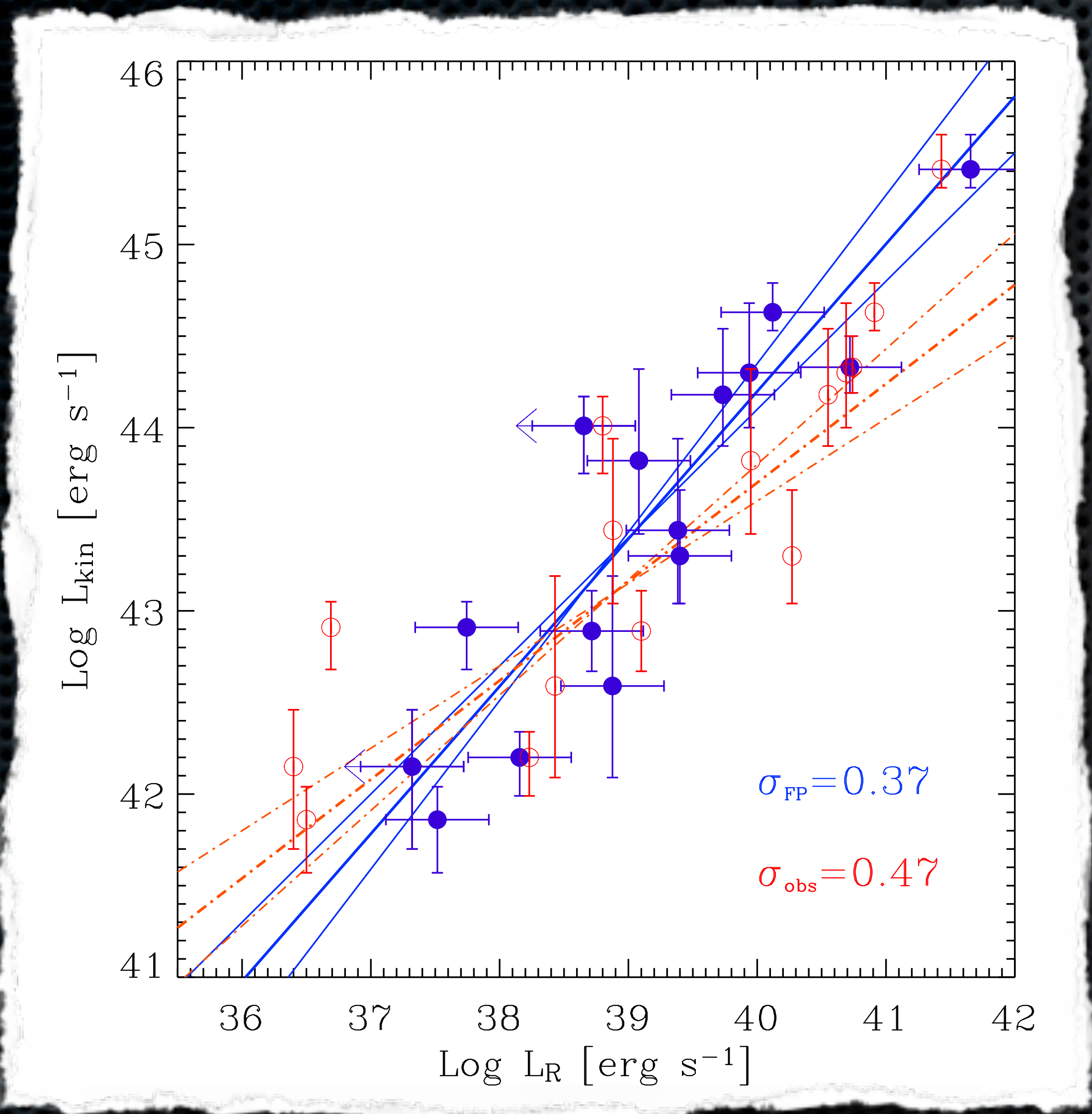
Bubble statistics

- Jet power vs. cluster cooling rate



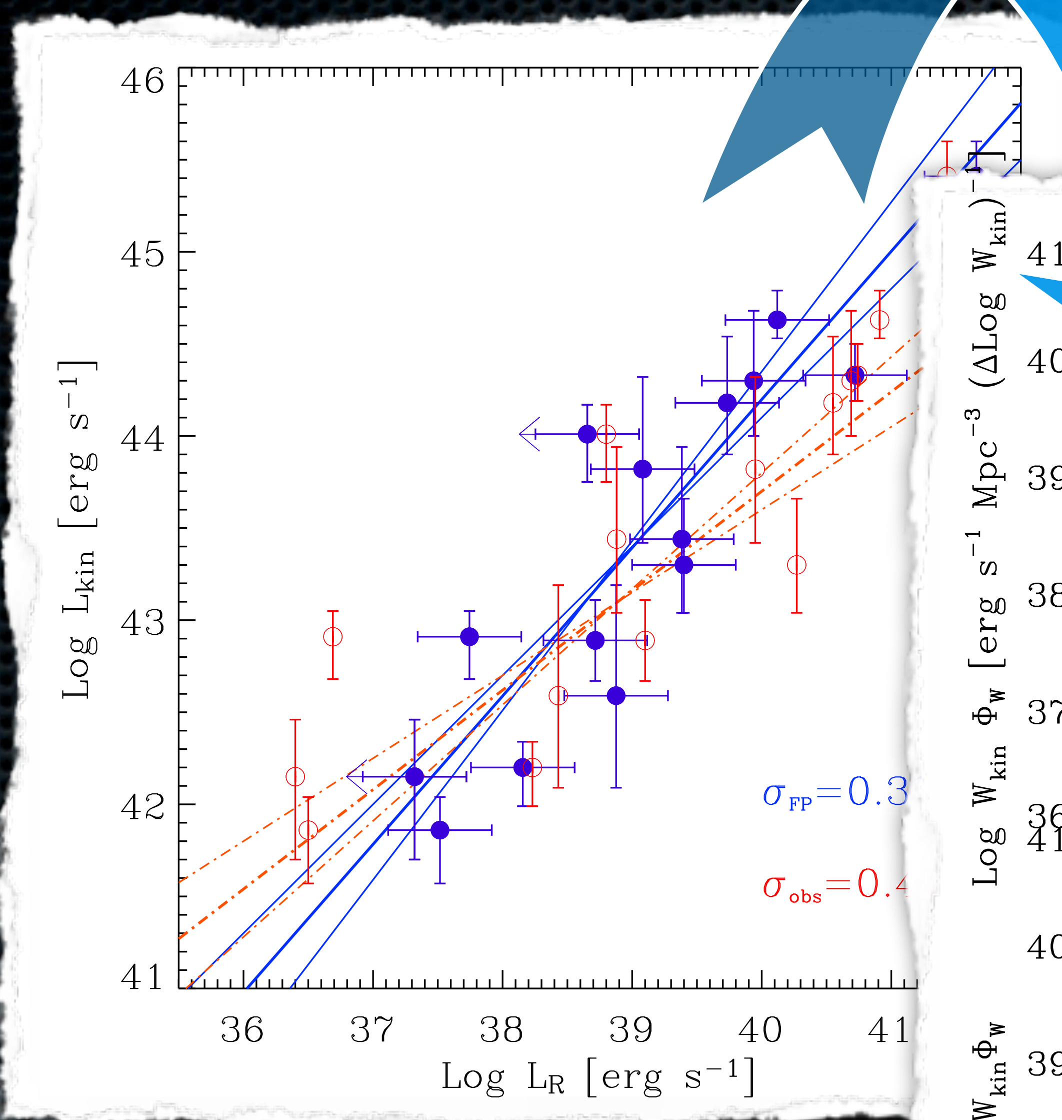
Rafferty et al. 2006

Global efficiency



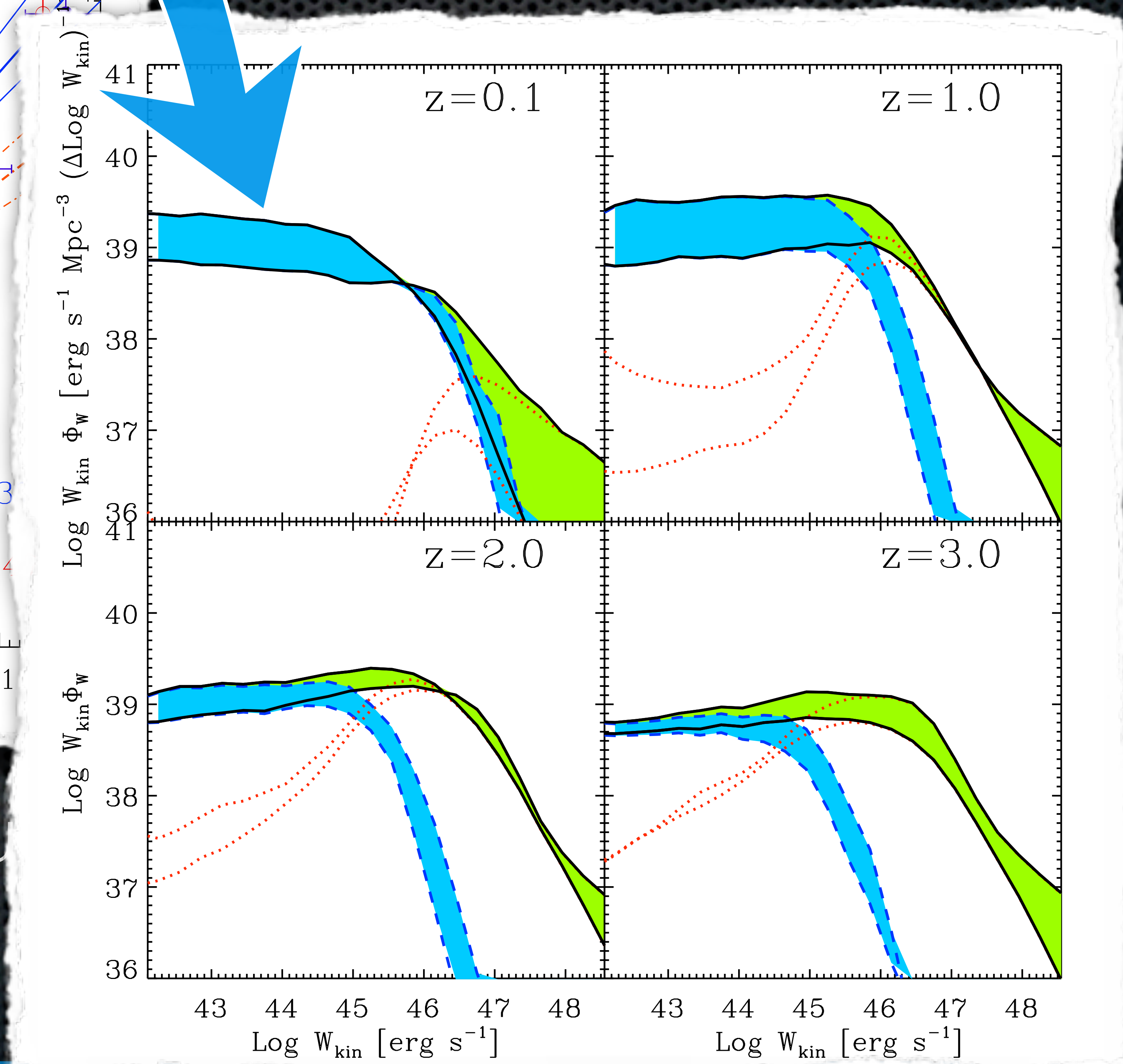
Jet power vs. core flux

Global efficiency



Jet power vs. core flu

Kinetic luminosity function

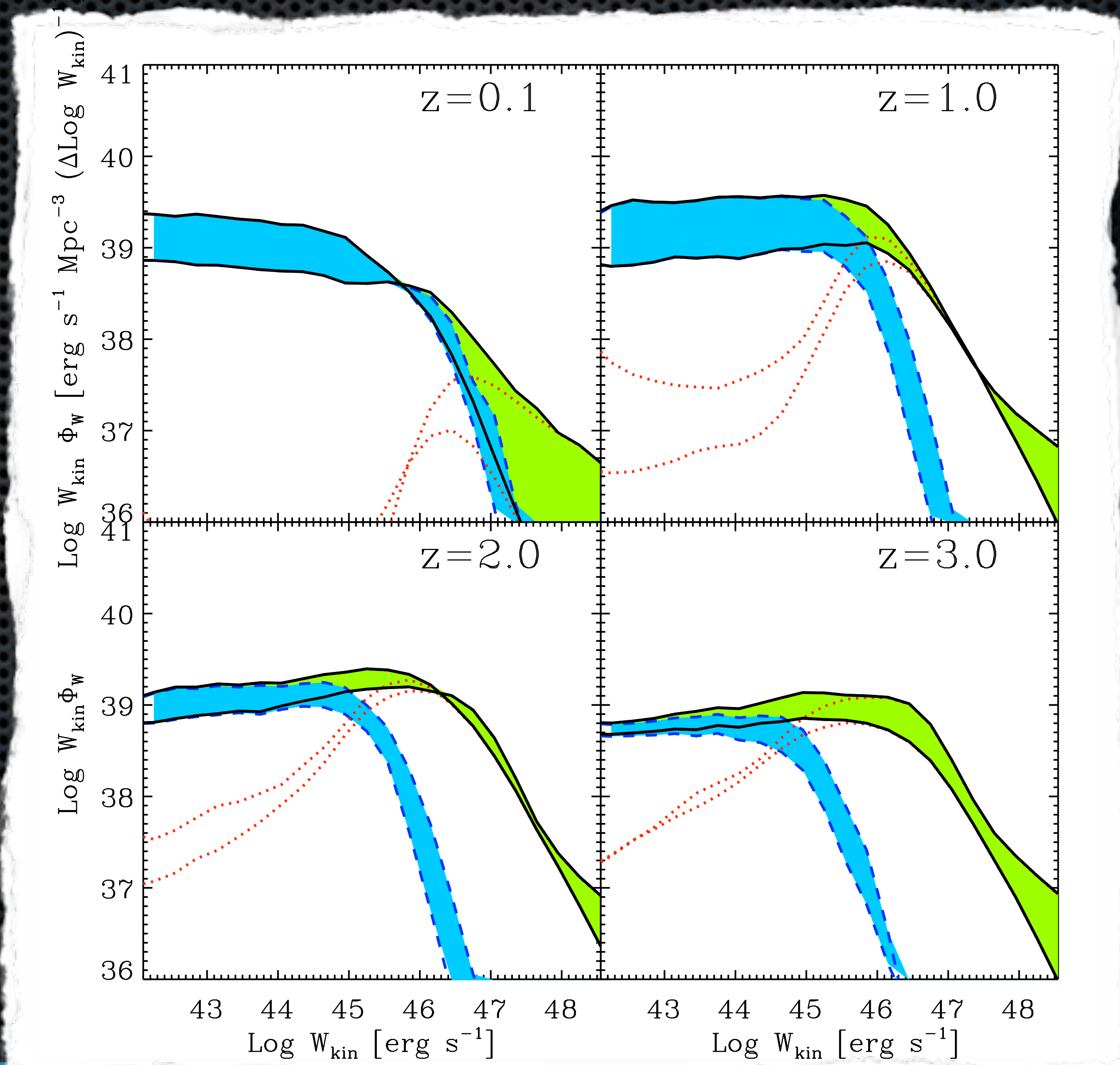


e.g., Merloni & Heinz 2009,2011

Global efficiency

- Low L sources
- $\langle \rho_{P_{jet}} \rangle \sim 10^{40} \, \frac{\text{ergs}}{\text{s cm}^3}$
- $\langle \eta \rangle \sim 0.2\% - 0.5\%$

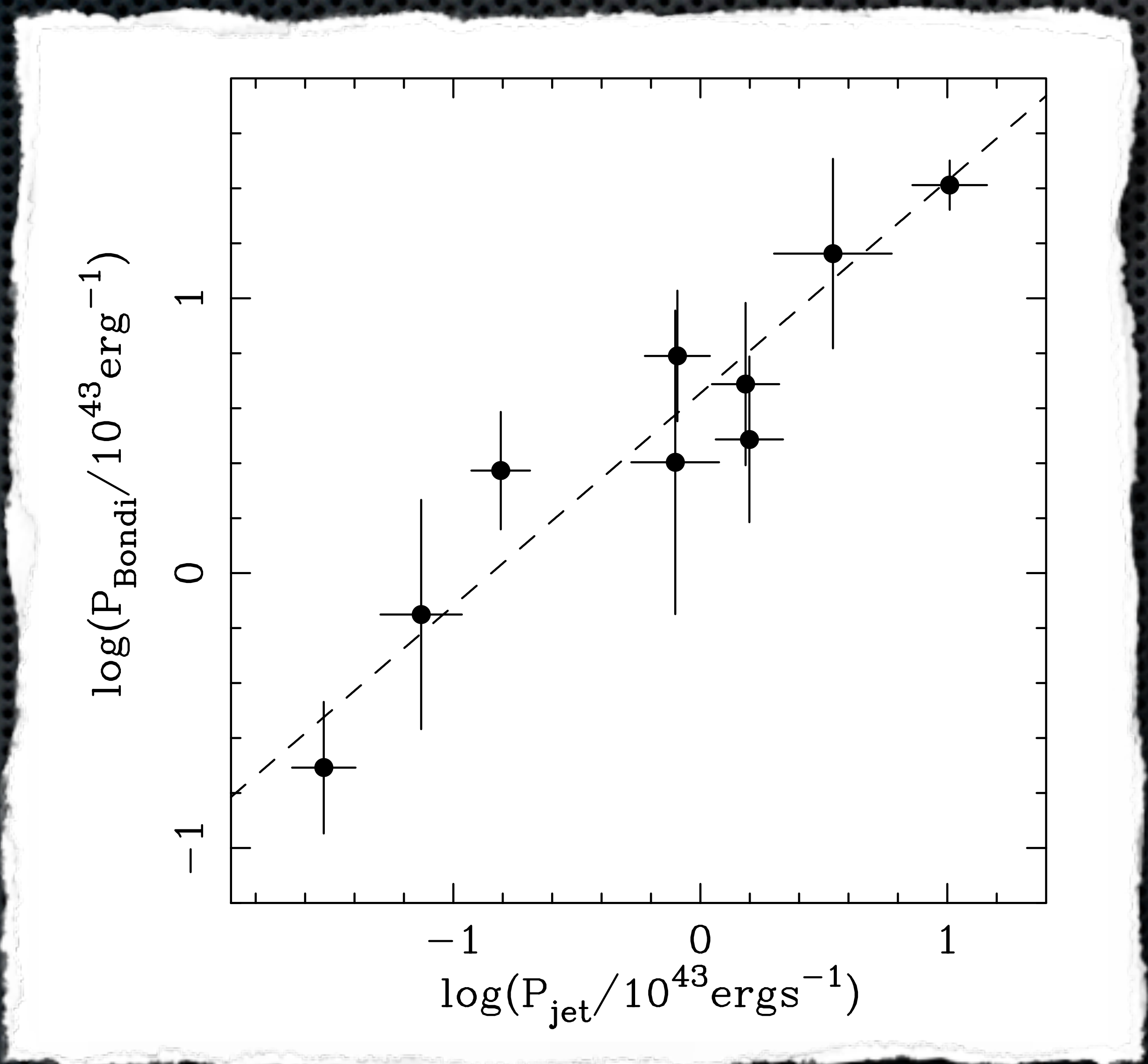
Kinetic luminosity function



e.g., Merloni & Heinz 2009,2011

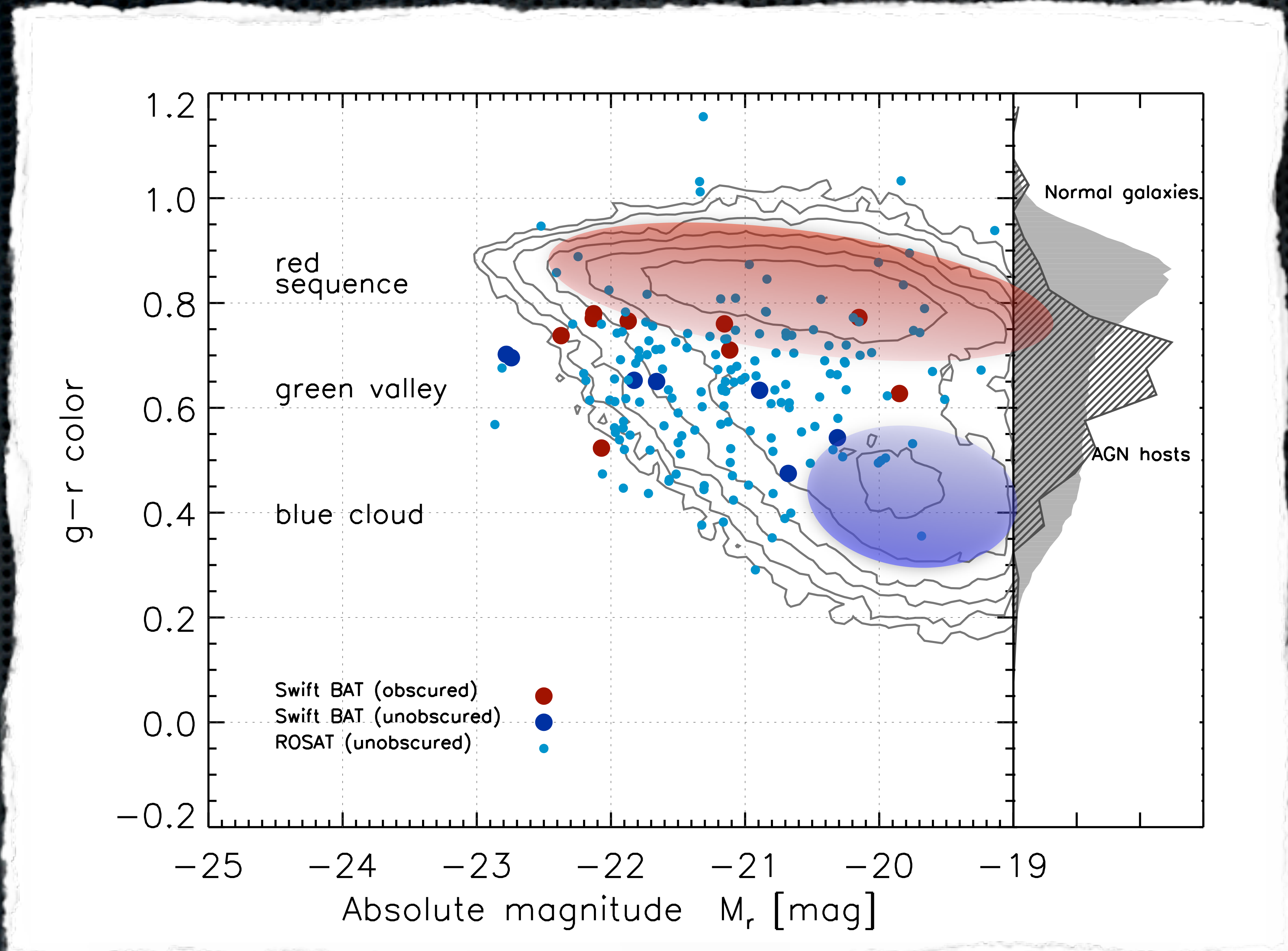
Bubble statistics

- Jet power vs. Bondi accretion rate: few% conversion?



Allen et al. 2006

“Radio mode” feedback?



Croton et al. 2006, Schawinski et al. 2009

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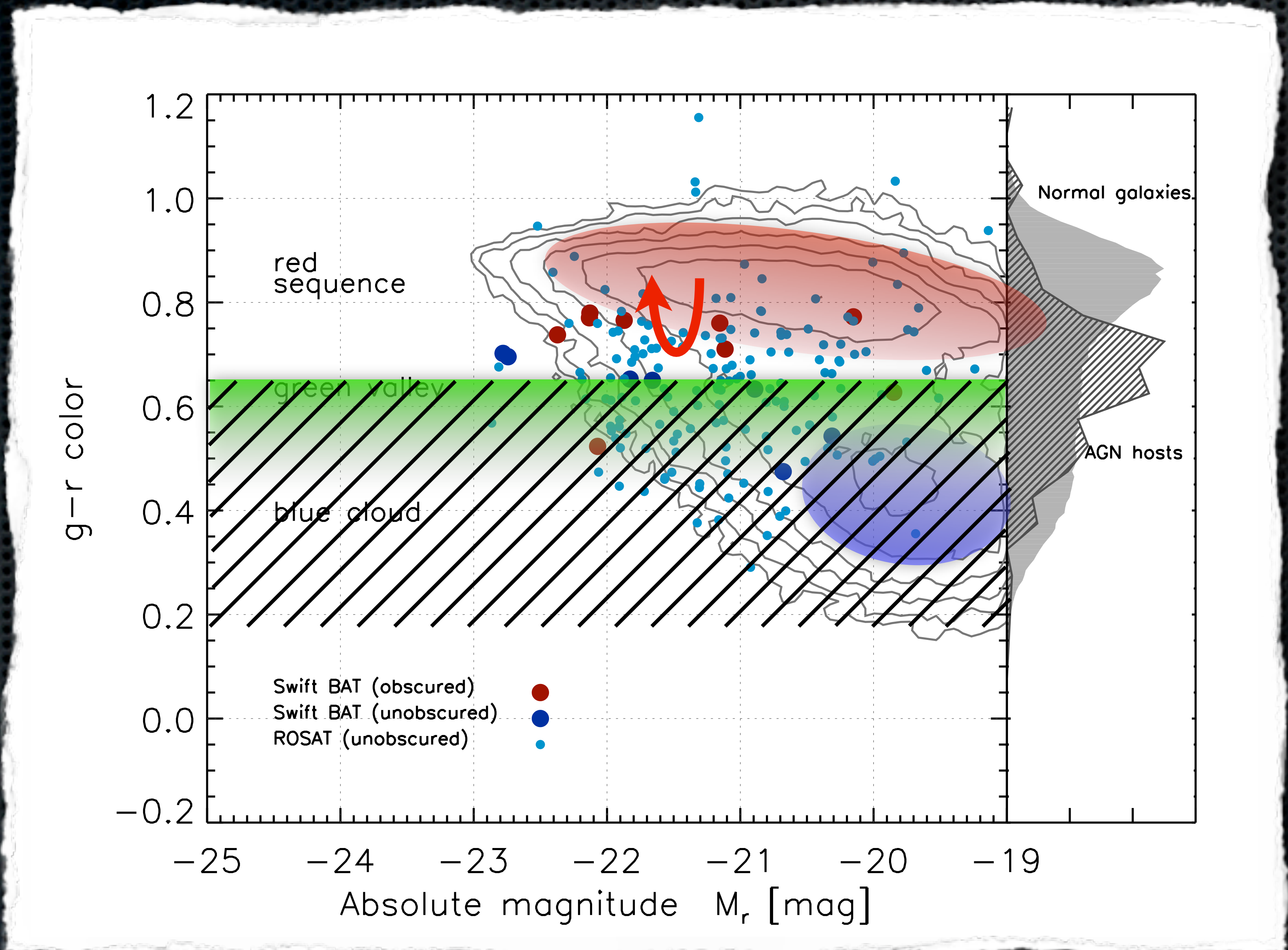

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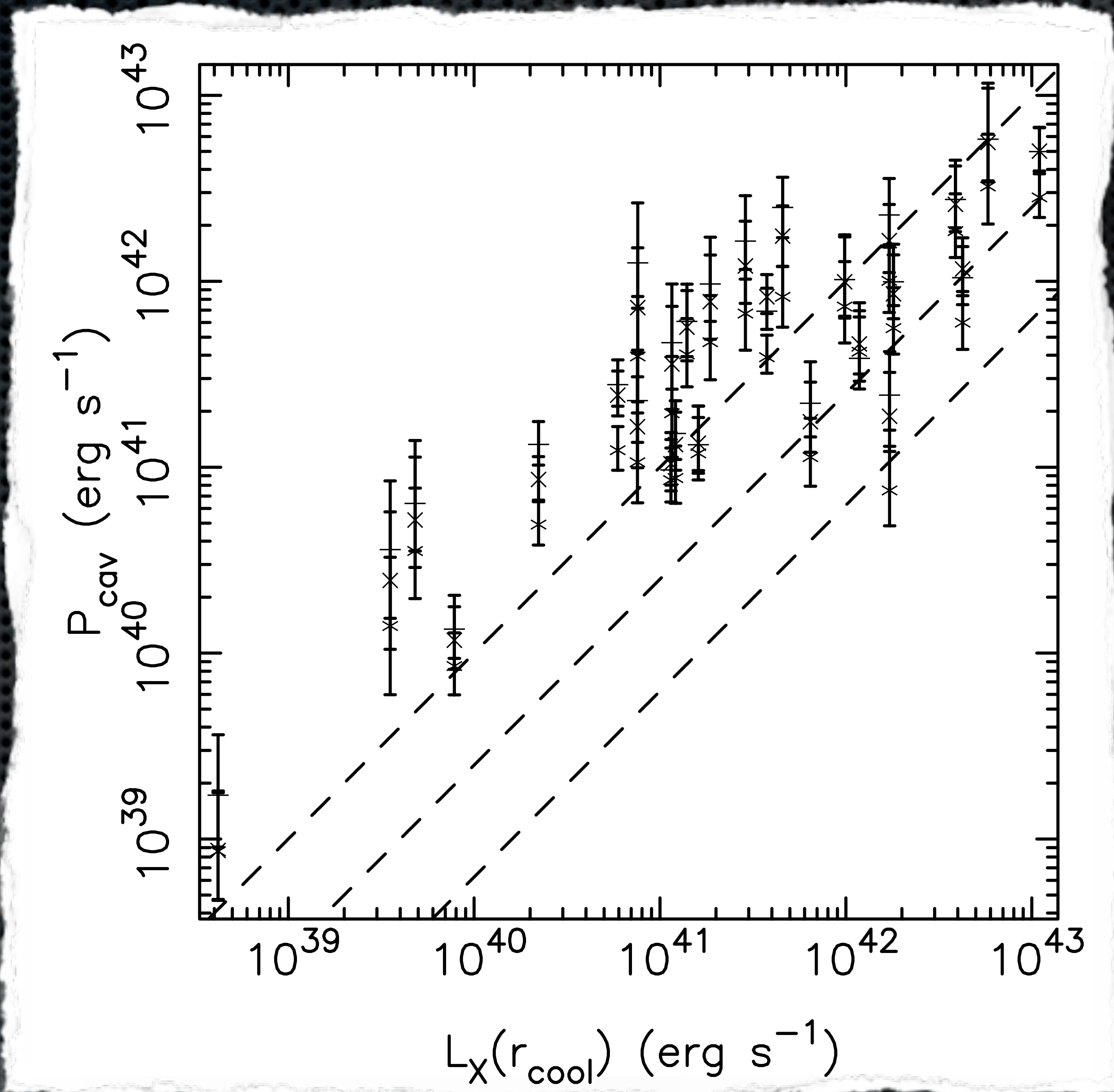
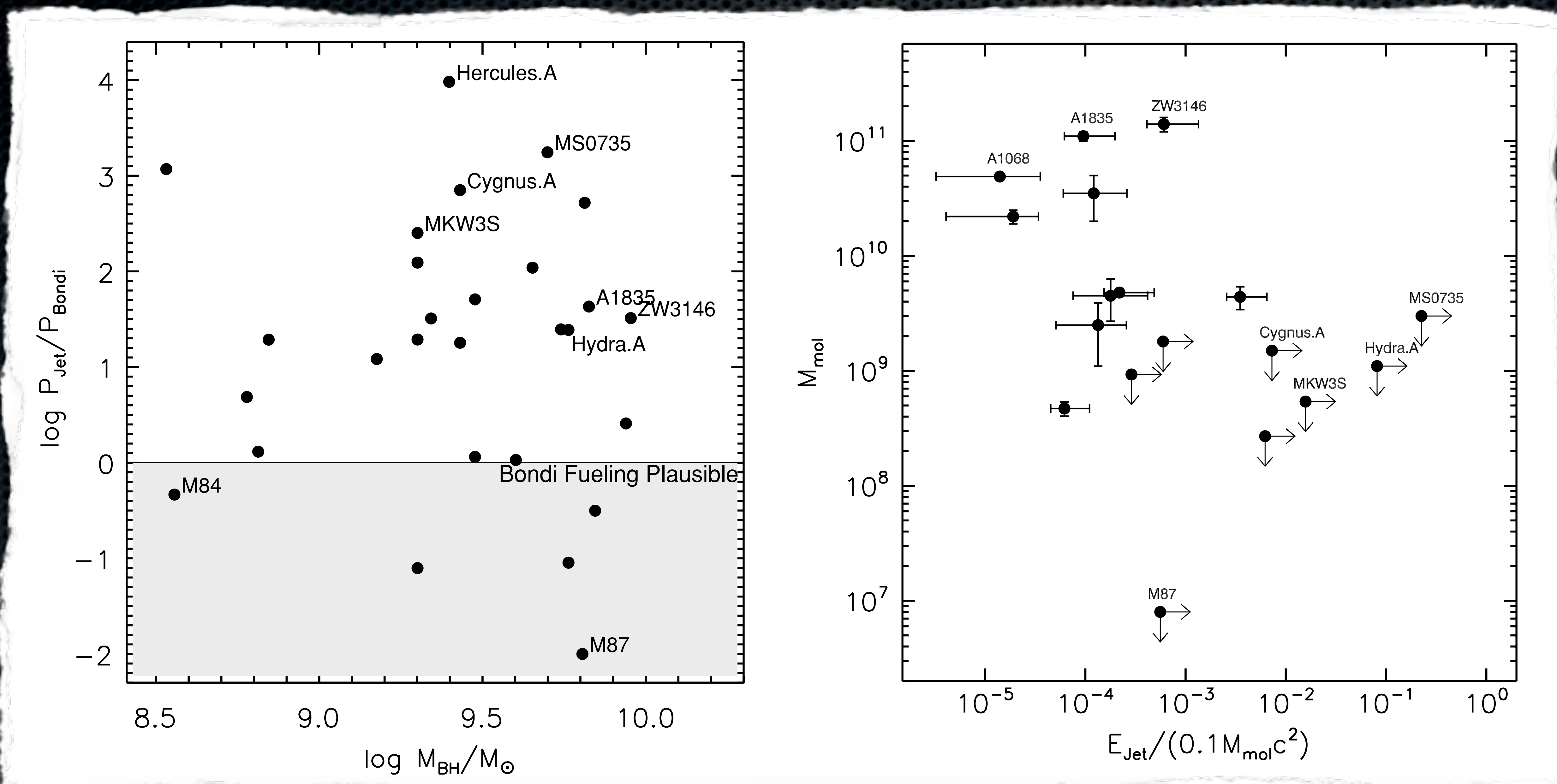


McNamara & Nulsen 2007

Spin?



McNamara et al. 2011

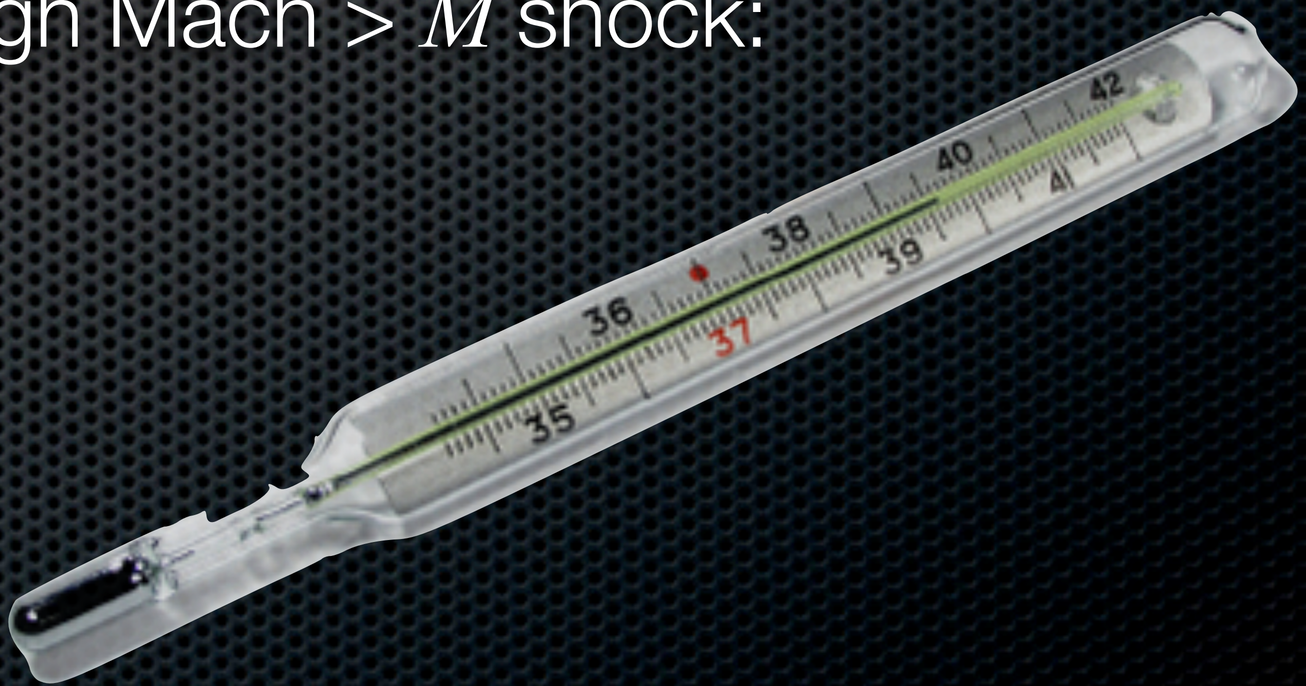
Cluster heating

- Shocks are out:
  - Fraction of time spent above Mach M

$$f_{\rm t}(>M) \sim \frac{M^{-2.5}}{3}$$

  - Mass fraction going through Mach > M shock:

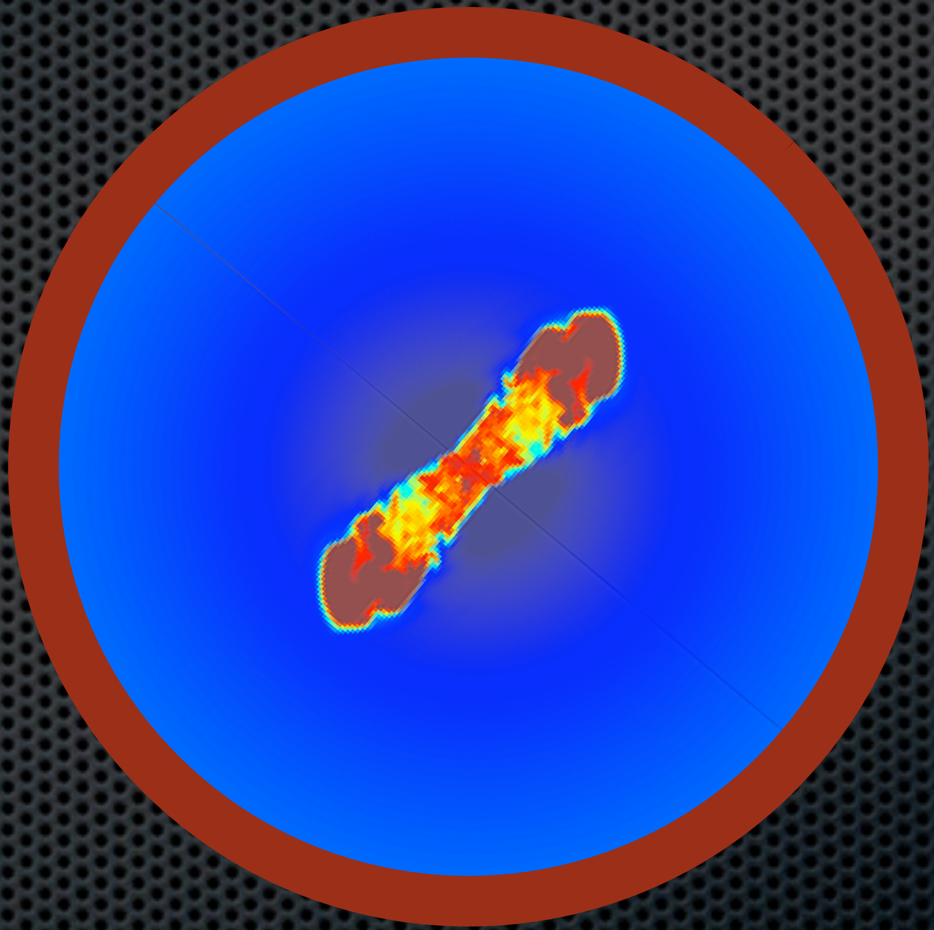
$$f_{\rm m}(>M) \sim \frac{M^{-9.5}}{3}$$



Merloni & Heinz 2011

“Central” question:

- How can a collimated bipolar jet heat a spherical cluster?



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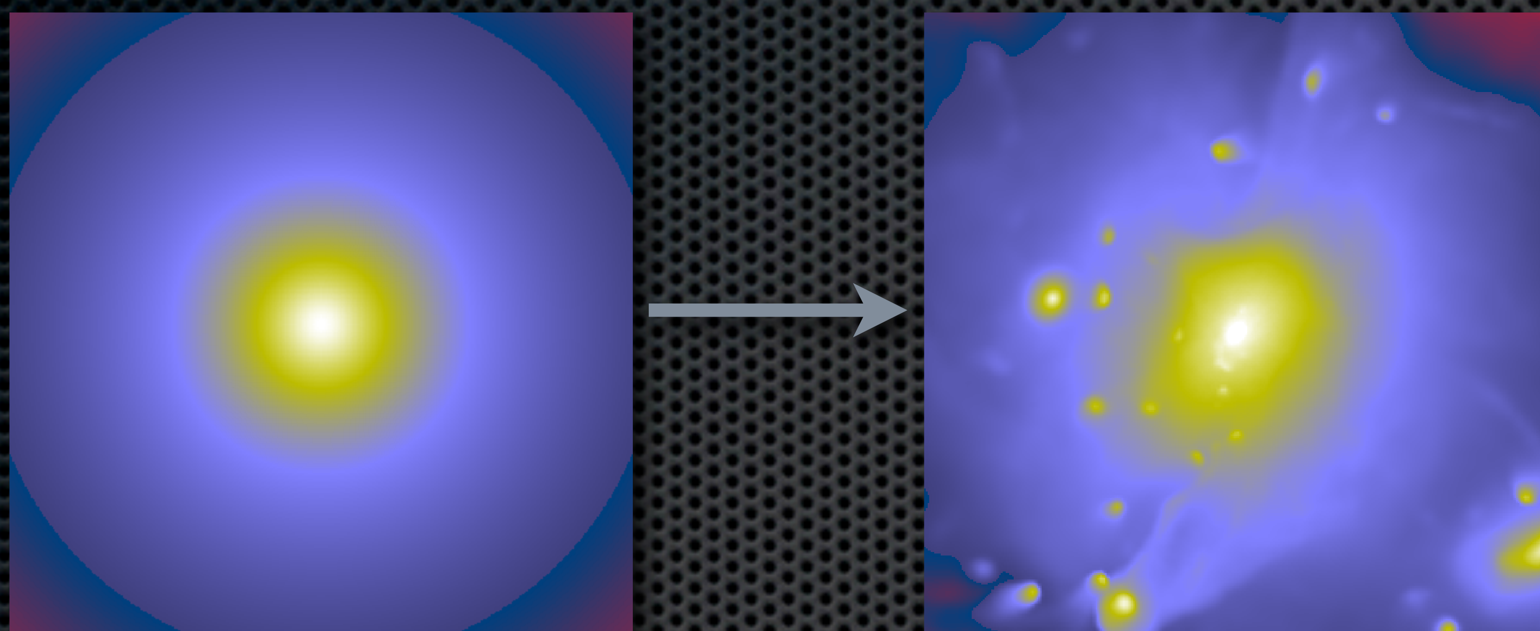
e.g., Vernaleo & Reynolds, 2006

Non-spherical clusters

- How much do Initial conditions in jet simulations matter?



Springel et al. 2002

- Clusters are **anisotropic** & dynamic

⇒ Start with a cosmologically evolved cluster

Model setup

Heinz et al. 2006, Morsony et al. 2010

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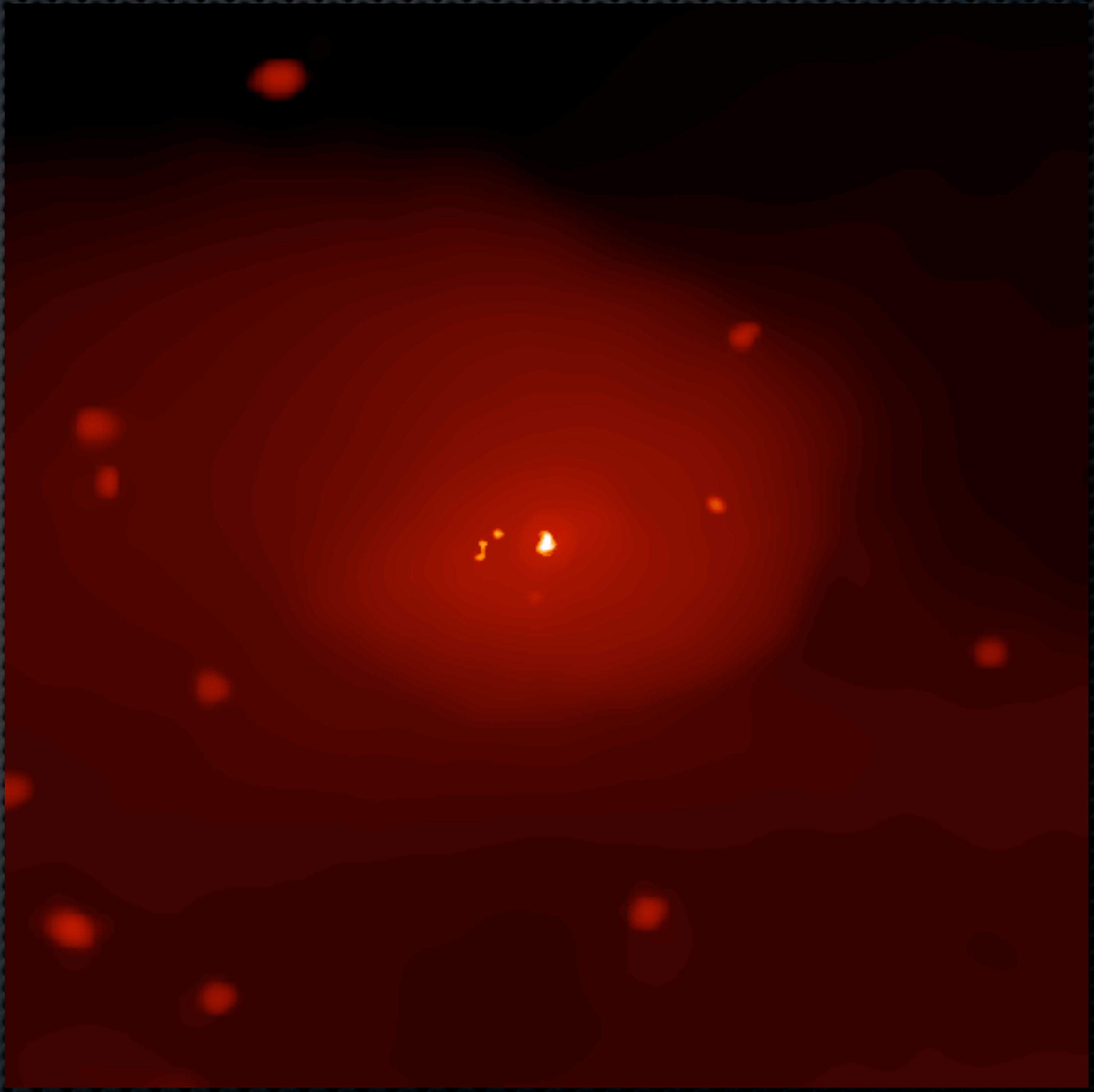

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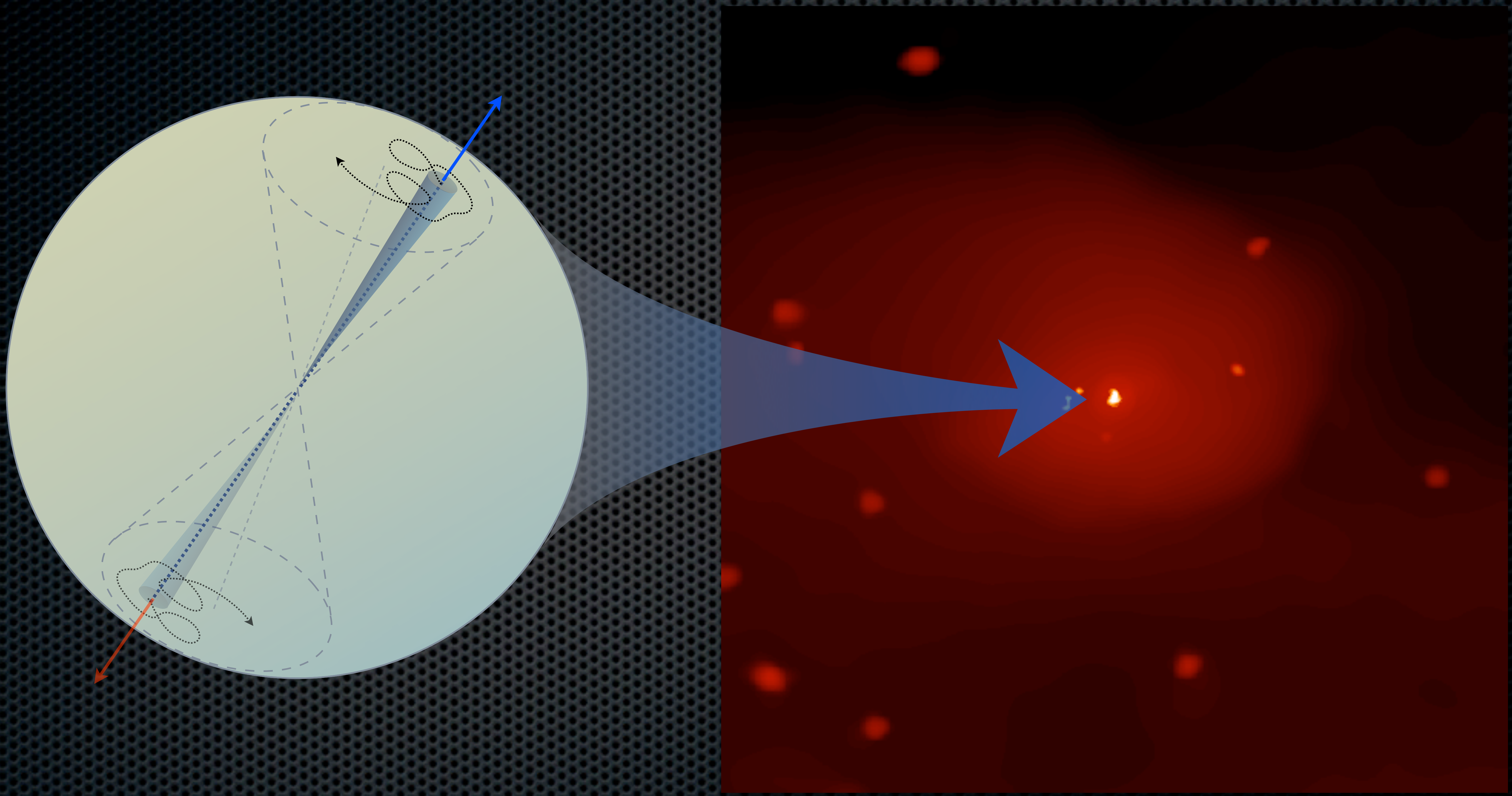

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The VLA view of Cygnus A[d]

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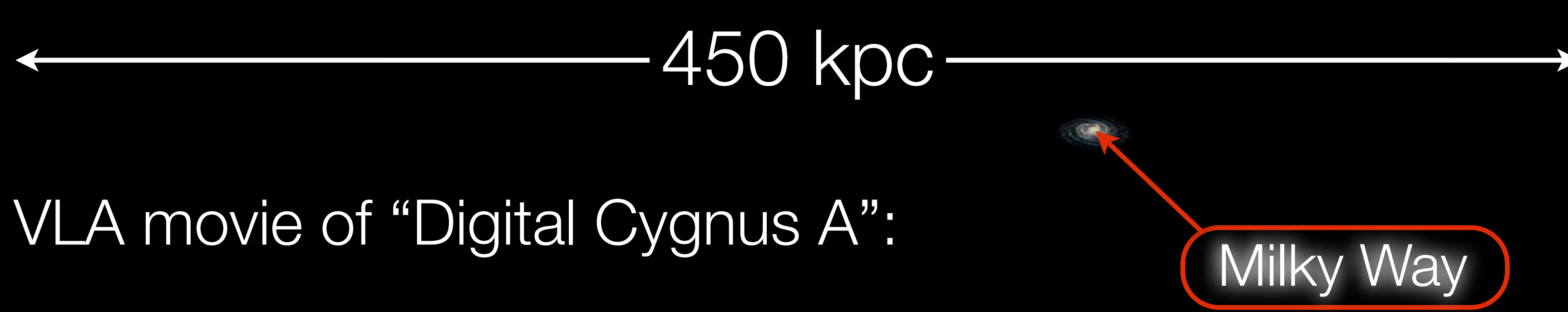
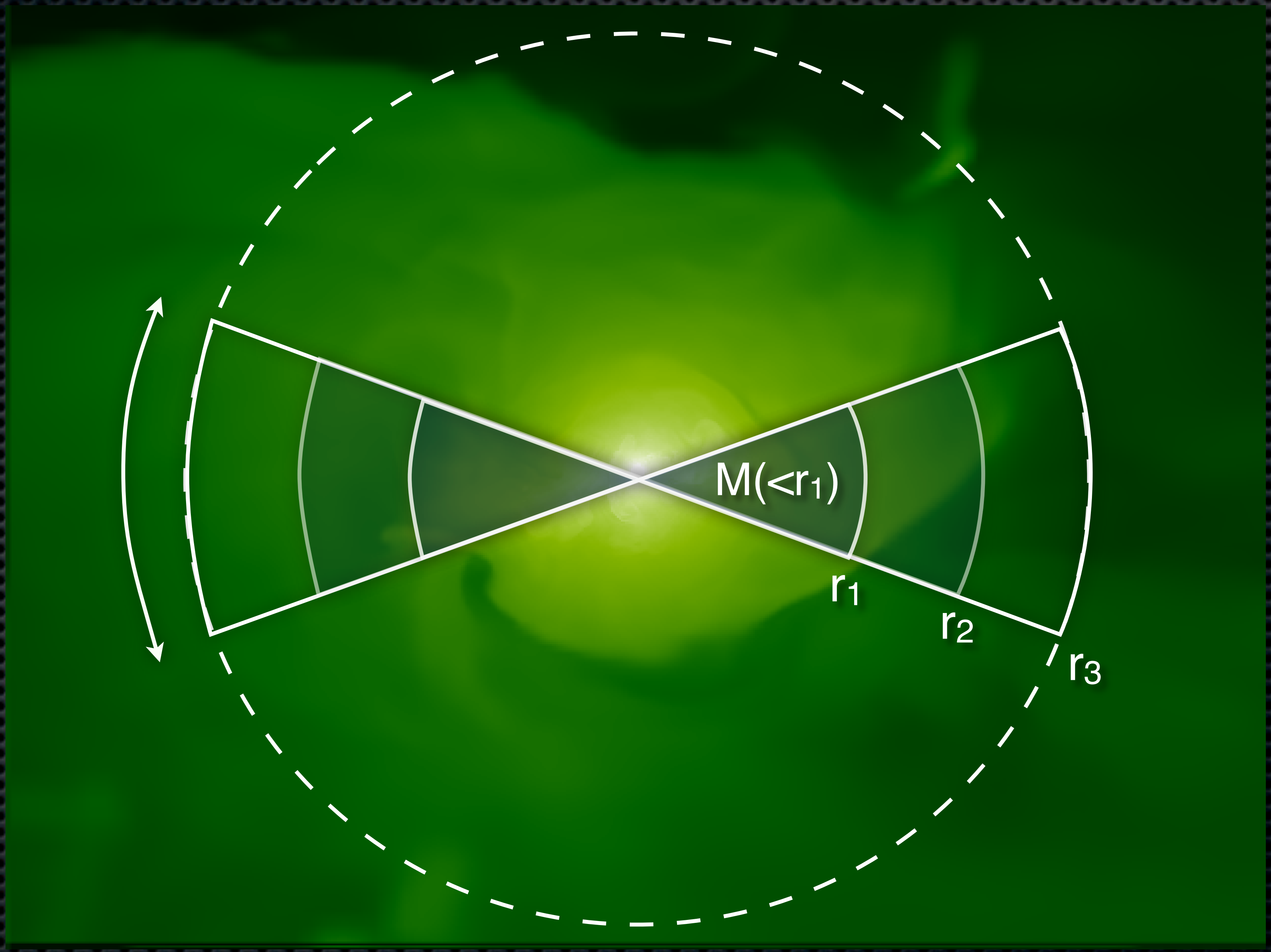


- Simulated VLA movie of “Digital Cygnus A”:
  - Simulated in a realistic galaxy cluster (from cosmo. sim.)
  - 10^{46} ergs s^{-1}
  - 160 Myrs
  - Resolution: 170 pc

Heinz, Brüggen, Young, & Levesque 2006

Jets vs. isotropy

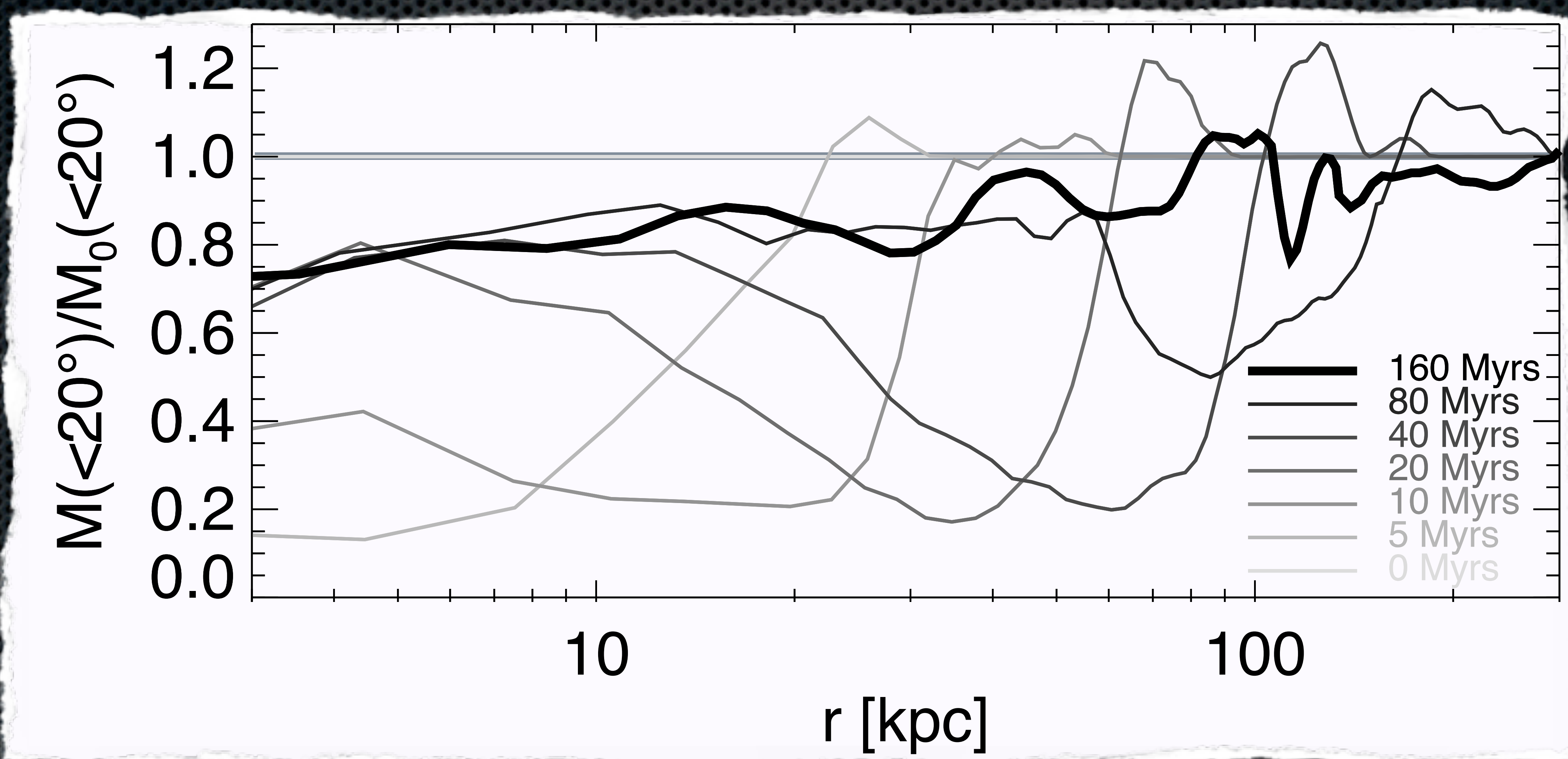
Relative mass depletion in jet channel:



Heinz, Brüggen, Young, & Levesque 2006

Jets vs. isotropy

- Rotation and dentist drill:
  - Jet channel re-filled after 80 Myrs
  - Subsequent jet episodes can couple with inner cluster



Multiple cavities ≠ intermittency

- Dynamics in cluster core:
  - "Target" material mixed into jet path
  - New cavities generated after ~ free fall time
  - Cannot use multiple cavities to infer duty cycle!

Morsony, Heinz, Brueggen, & Ruszkowski 2010

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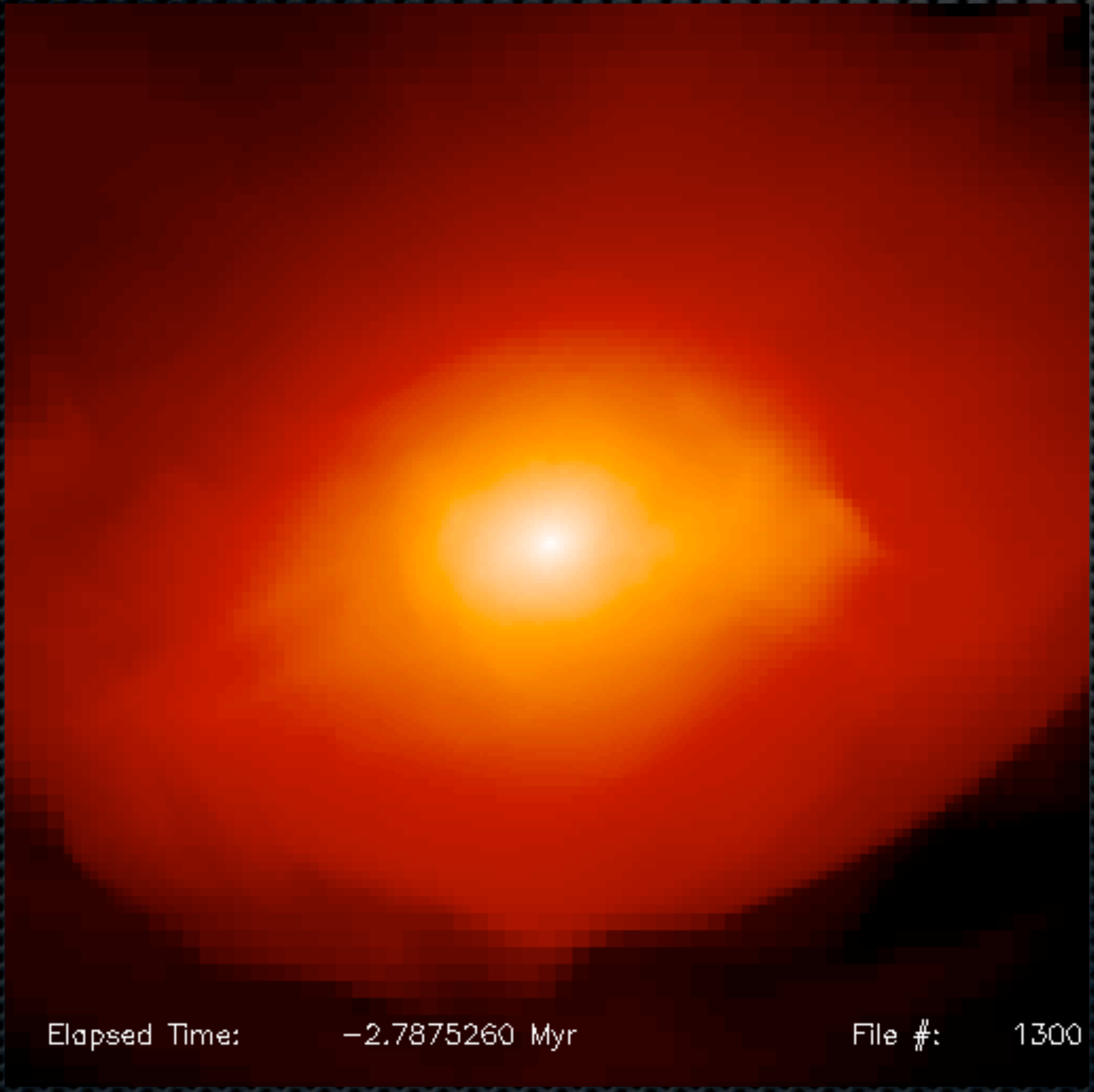

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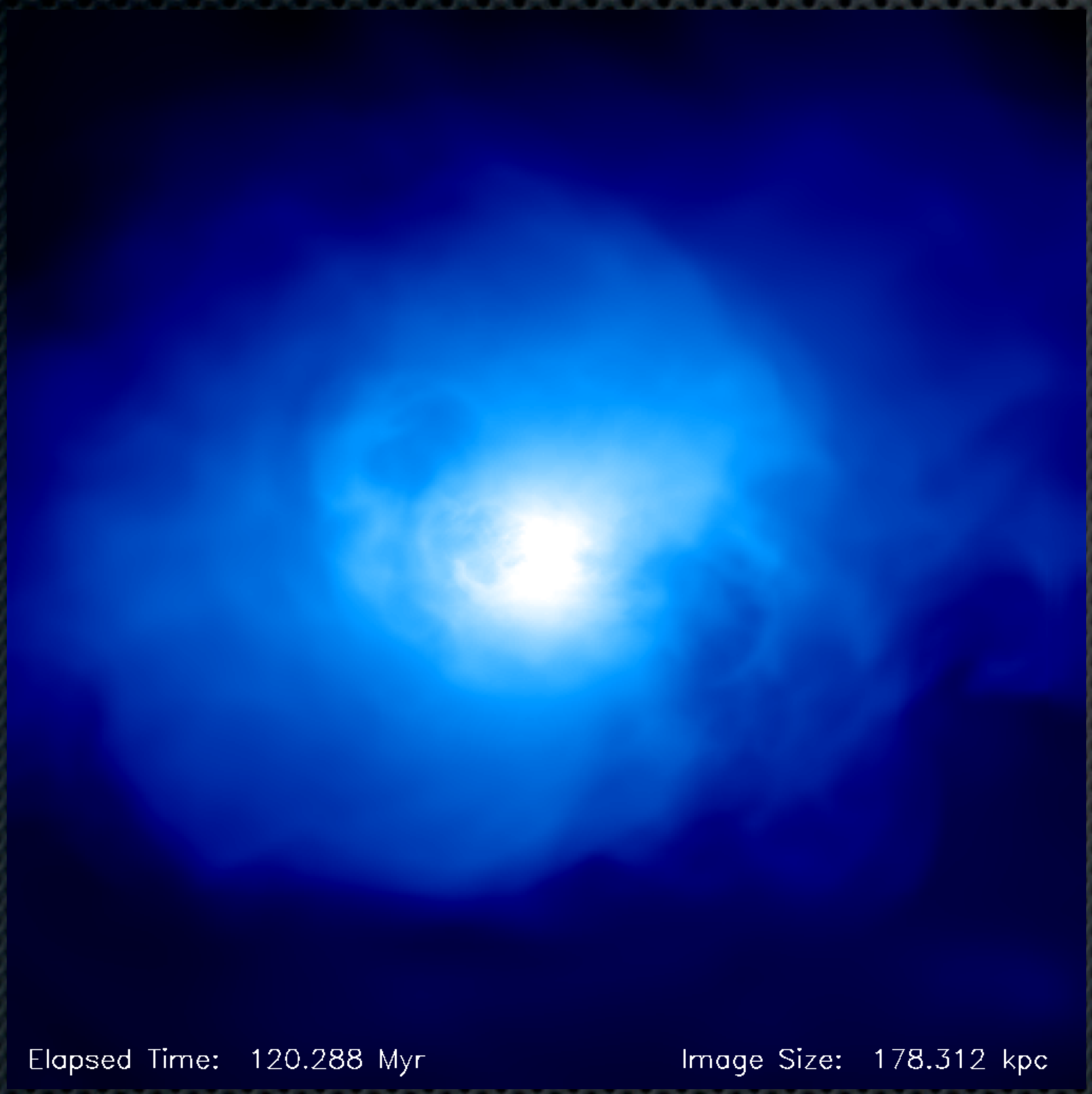

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Cluster weather: AGN sphere of influence

- Interaction with cluster weather
  - AGN impact limited to “sphere of influence”
  - Radius $R \sim P^{1/3}$
  - AGN excavates deeper, rather than further

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Elapsed Time: −2.7875260 Myr Image Size: 178.312 kpc

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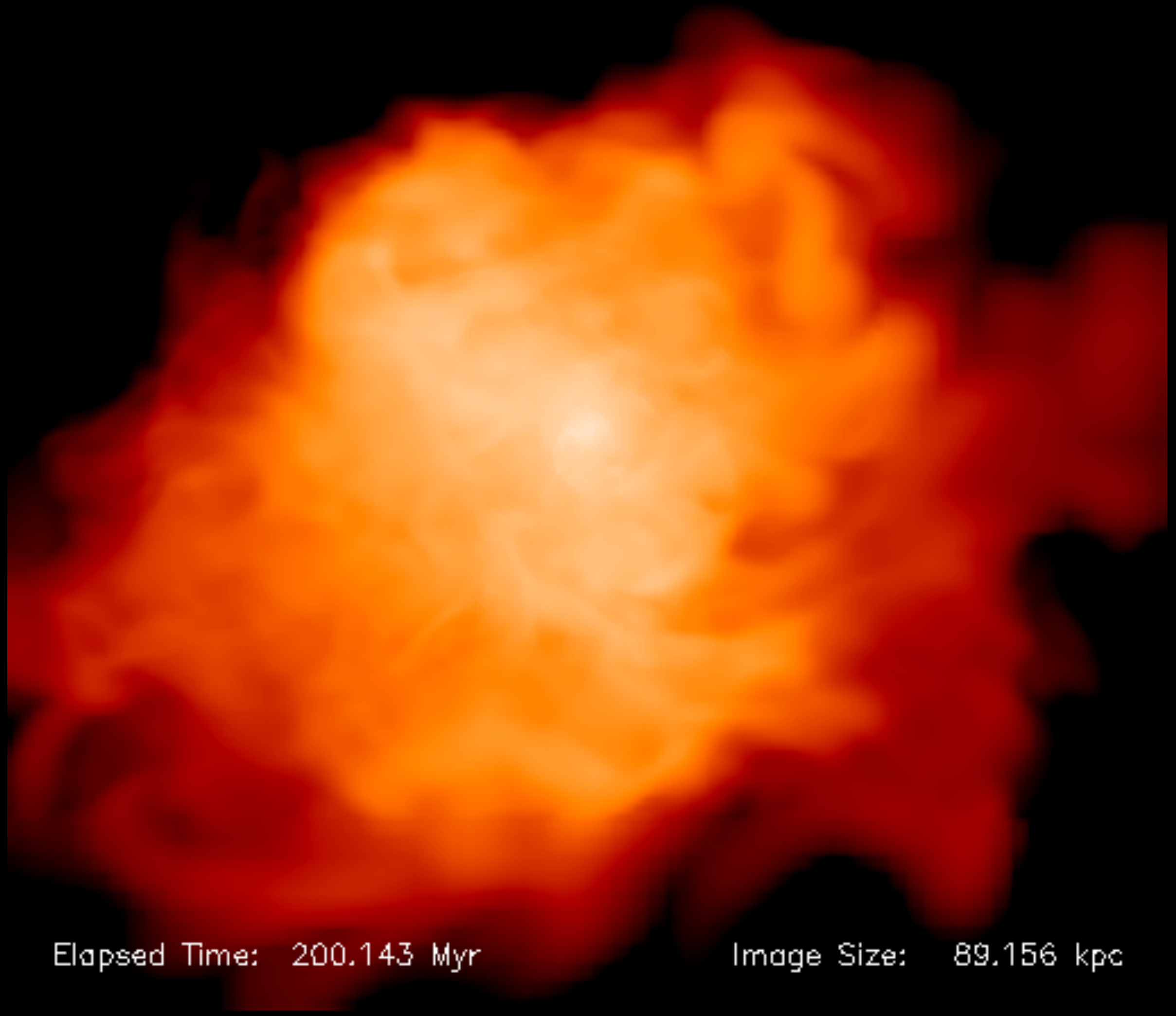

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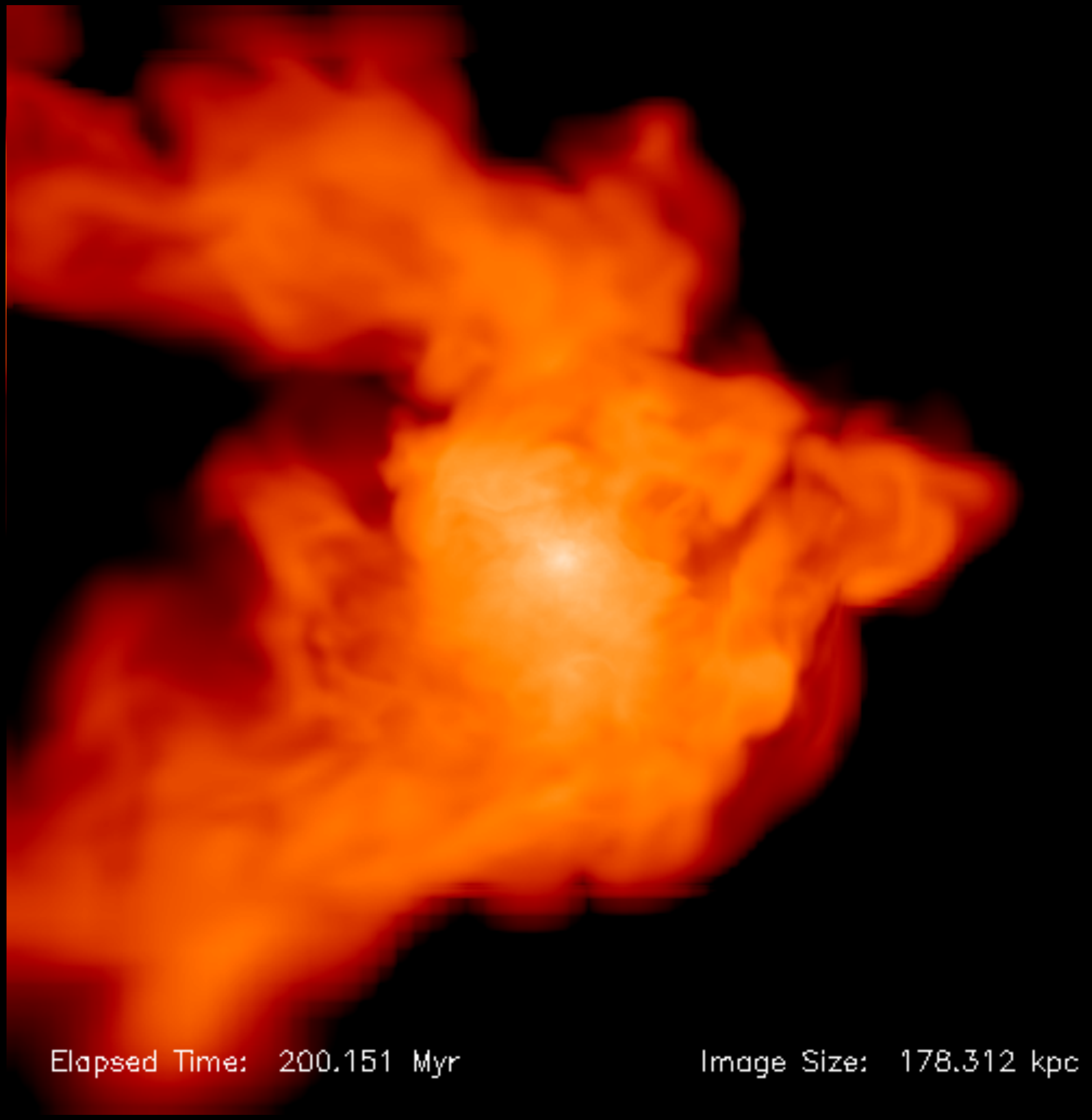

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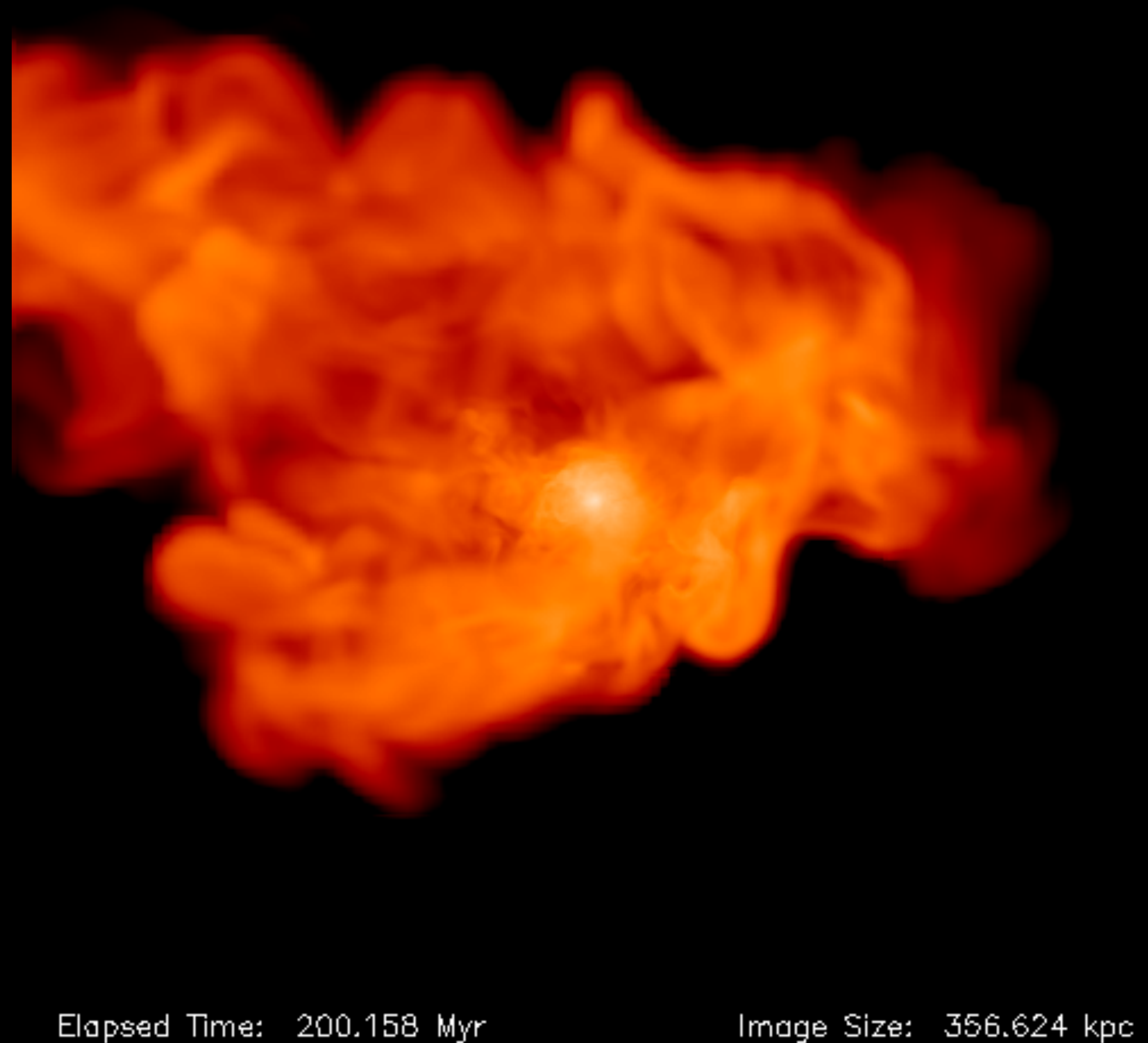
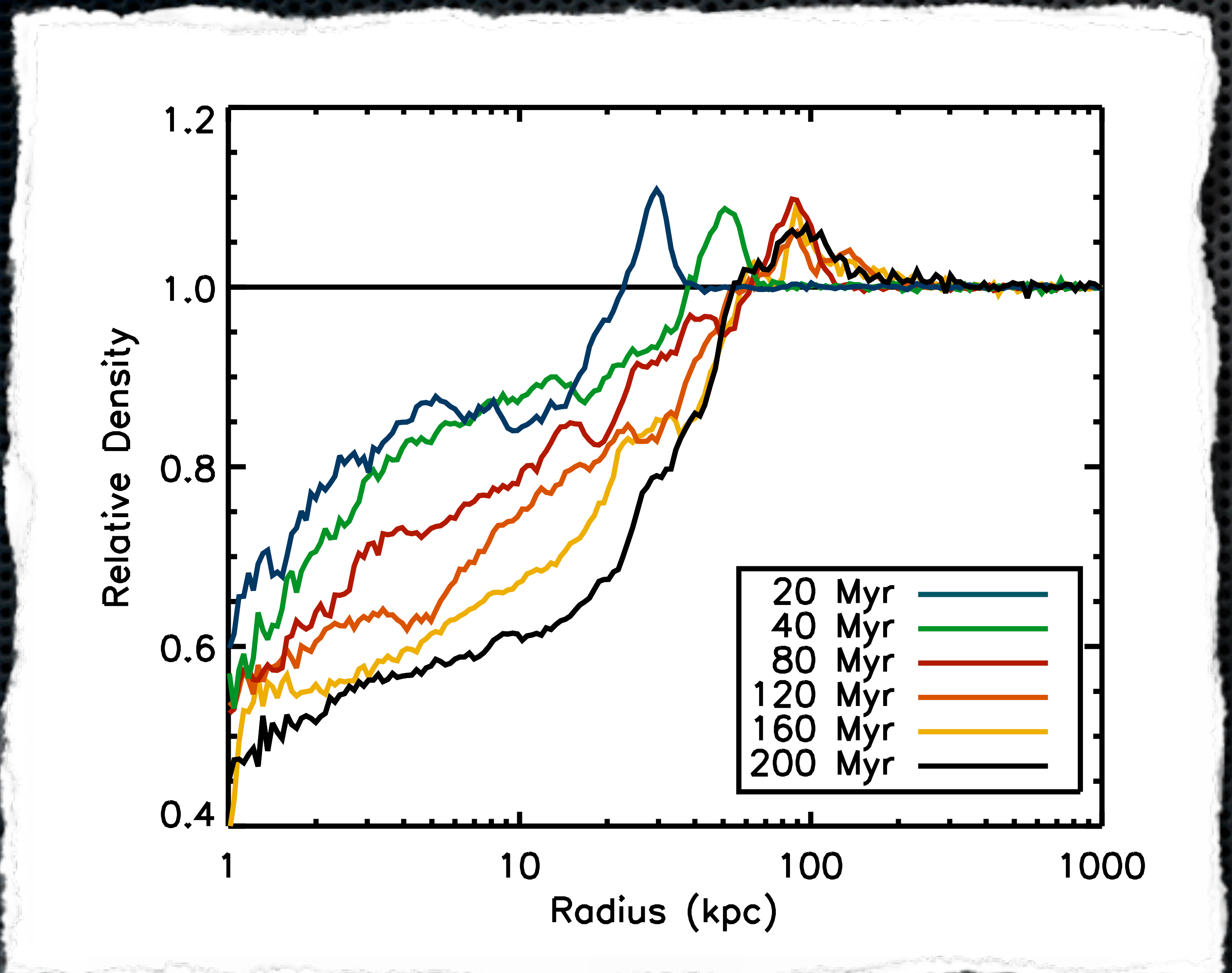


Morsony, Heinz, Brueggen, & Ruszkowski 2010

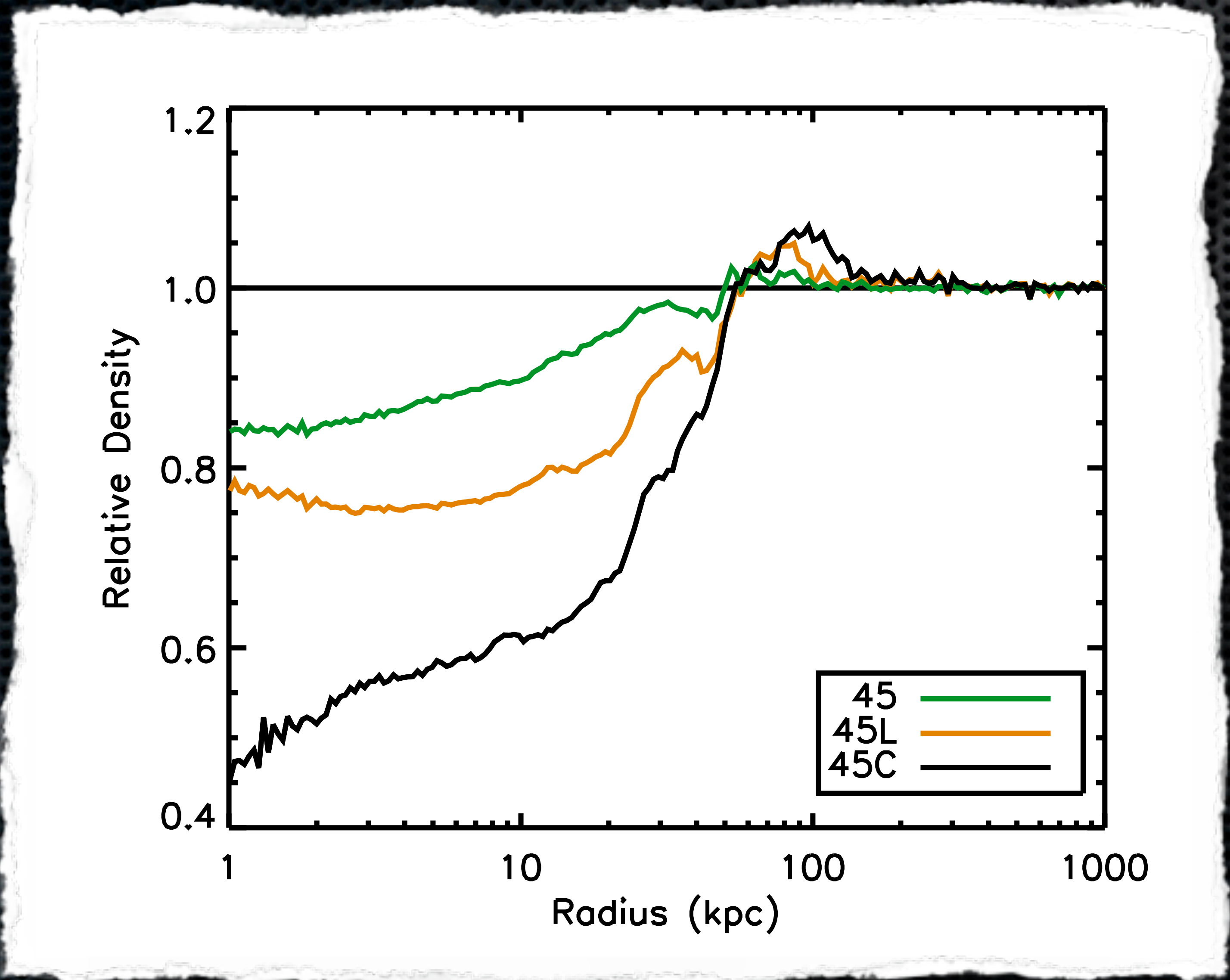
“Sphere of influence”: Time after onset



Morsony, Heinz, Brueggen, & Ruszkowski 2010

- Excavated zone reaches asymptotic terminal size

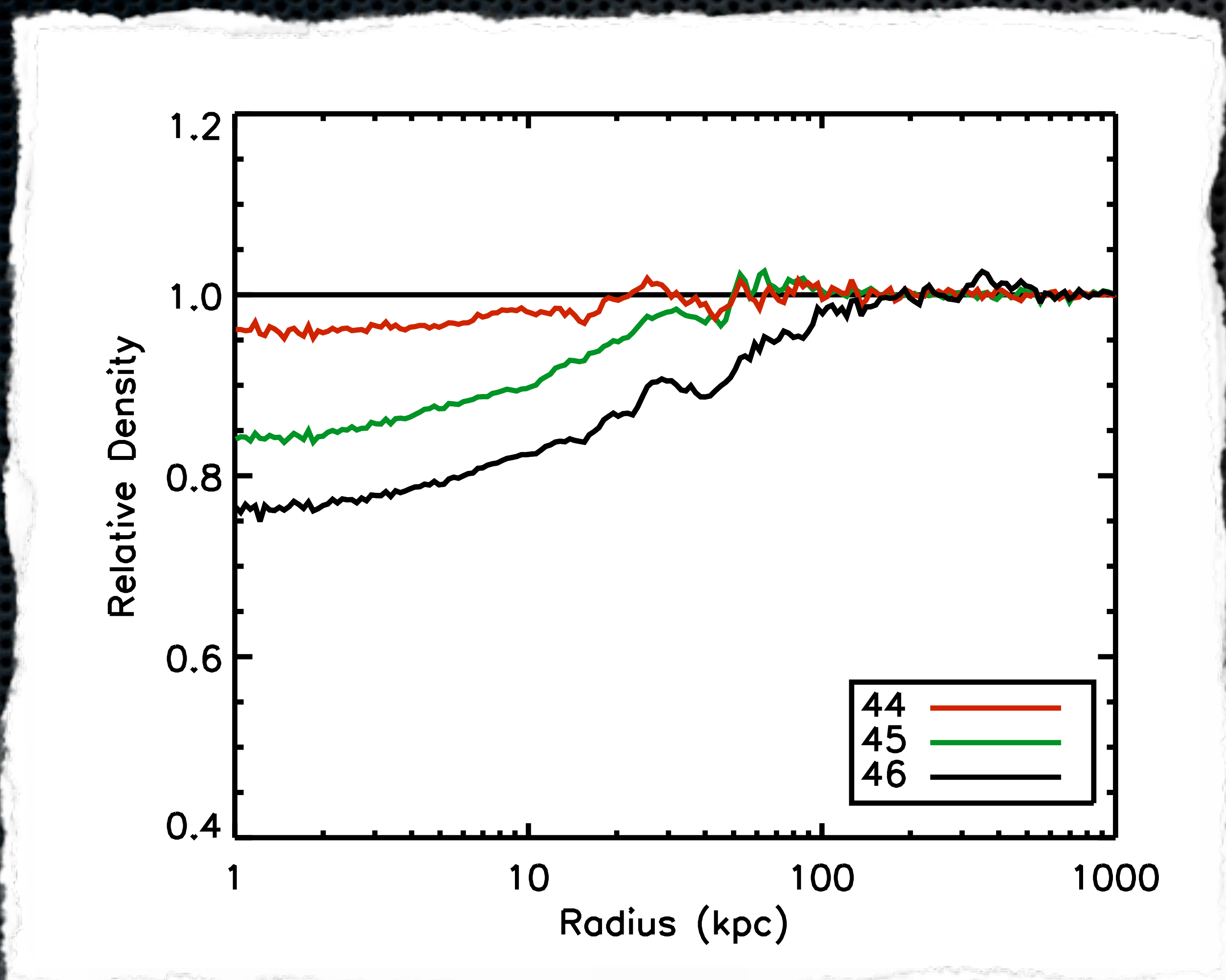
“Sphere of influence”: Jet duration



Morsony, Heinz, Brueggen, & Ruszkowski 2010

- 1e45 ergs/s, on for
  - 30 Myrs
  - 50 Myrs
  - Continuously
- Excavated zone stationary, just deeper

"Sphere of influence": Jet power



Morsony, Heinz, Brueggen, & Ruszkowski 2010

- Comparison:
  - 1e44 ergs/s for 30 Myrs
  - 1e45 ergs/s for 30 Myrs
  - 1e46 ergs/s for 30 Myrs
- Excavated radius:
  - $R \sim P^{1/3}$

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  - Photons
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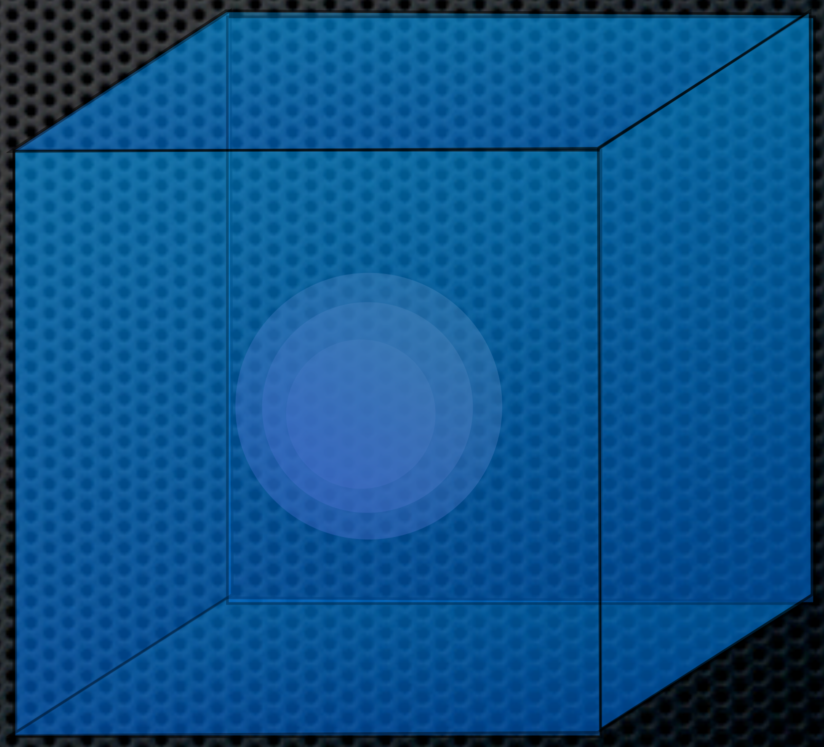
Interface: simulations/observations

A simulation is useless in vacuum, needs connection to observations

1. Take a 3D simulation of thermal gas

2. Simulate the spectrum emitted by the gas

3. “Observe” it with an X-ray telescope



Download: http://www.astro.wisc.edu/~heinzs/XIM

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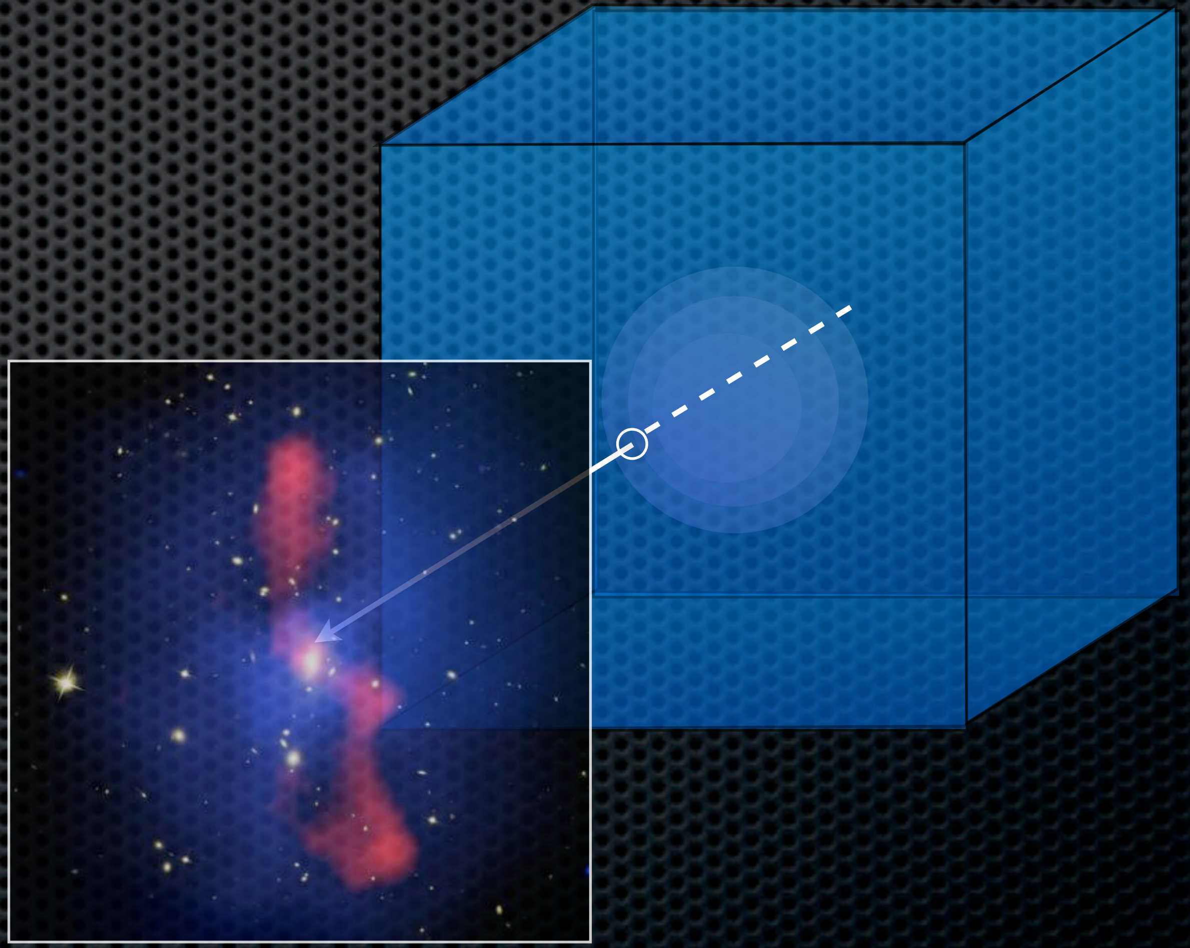

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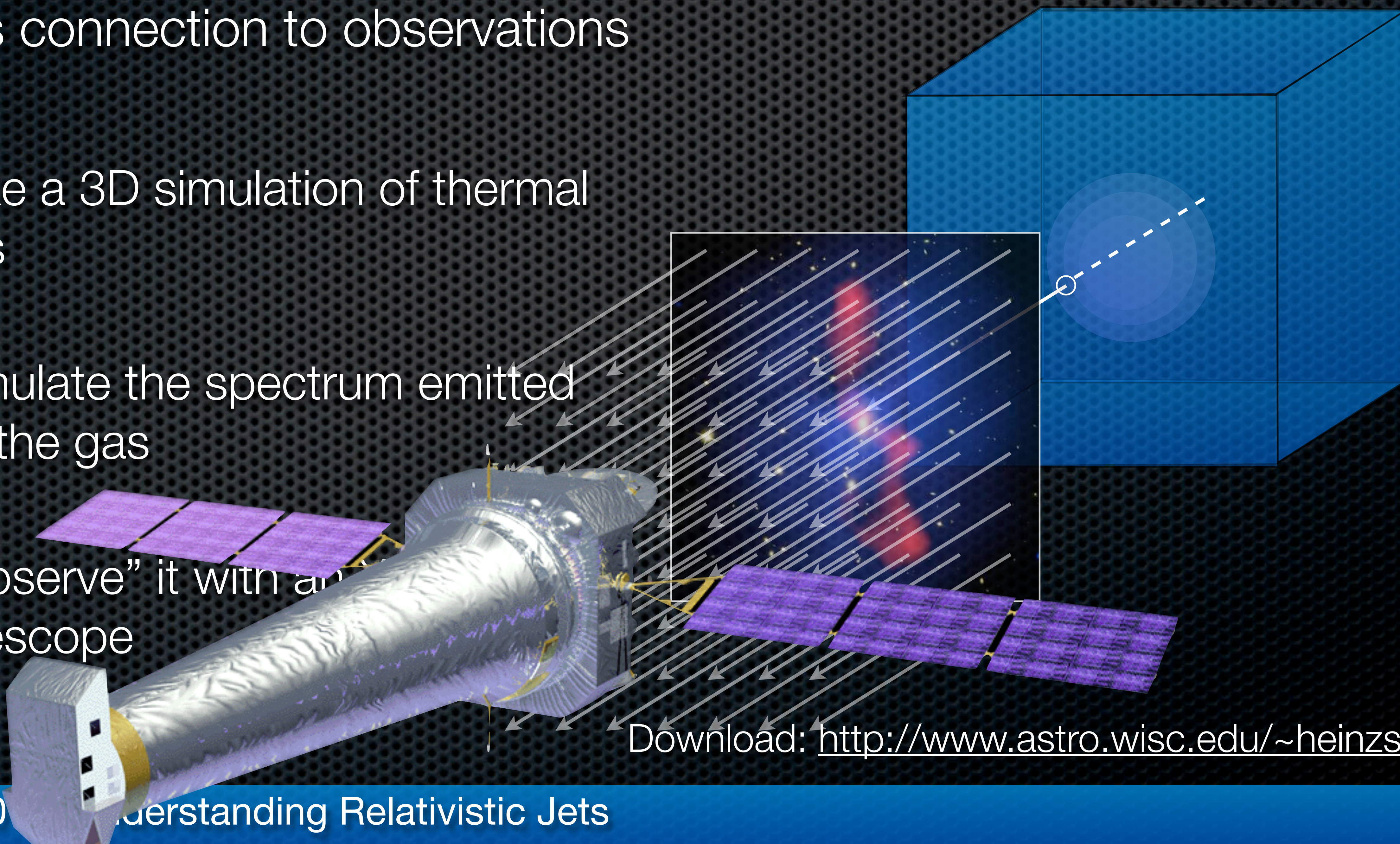

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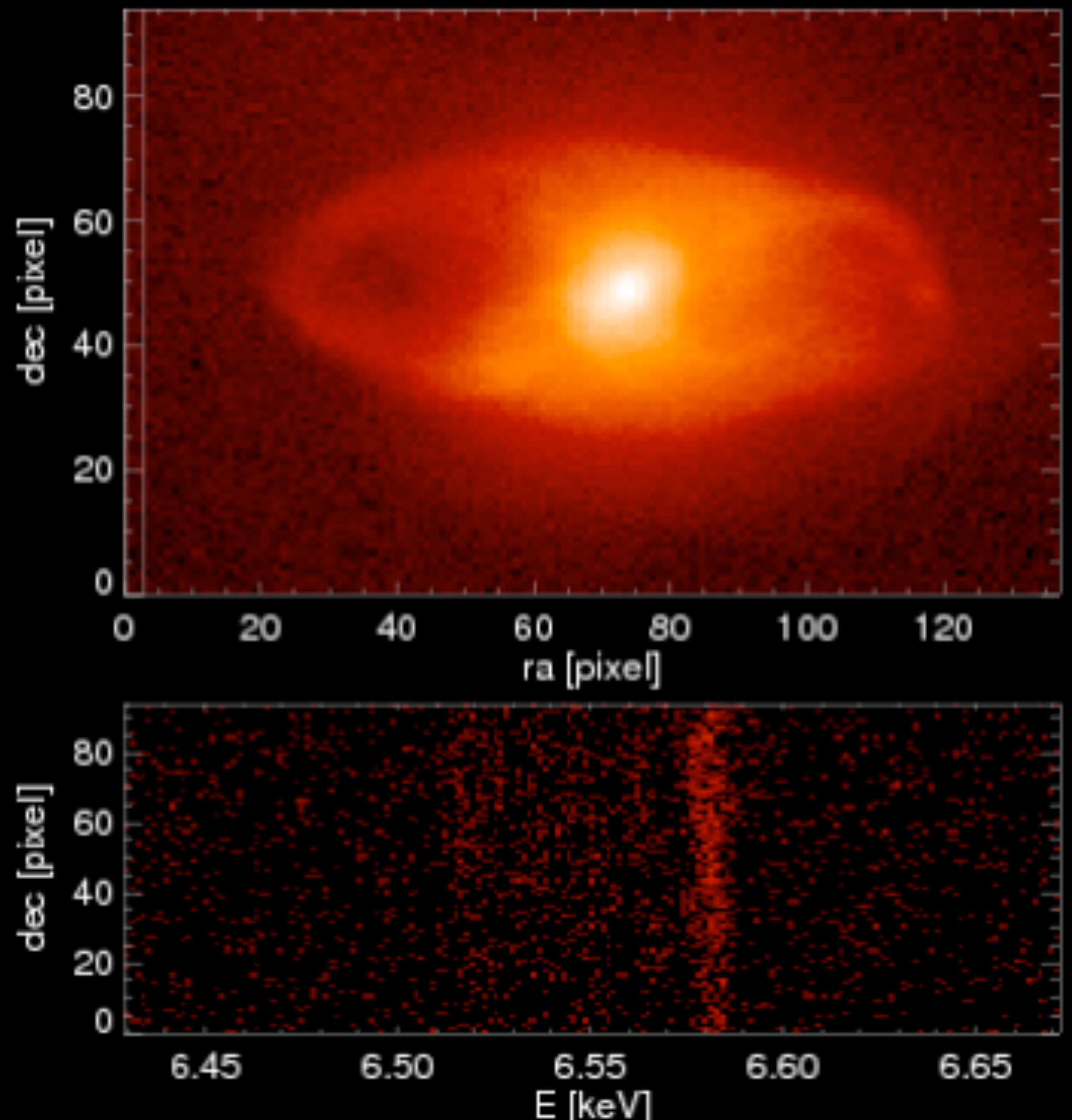
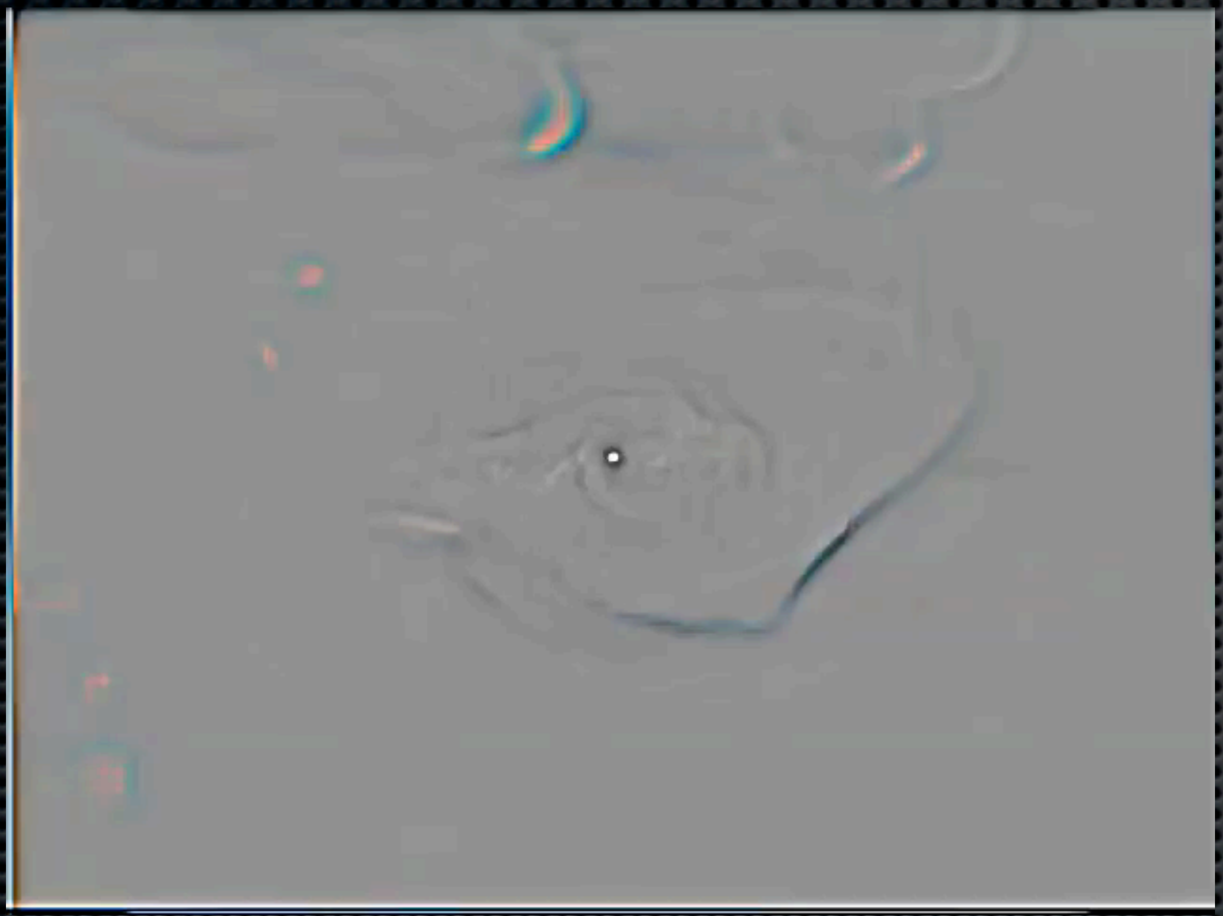


Jet-induced turbulence



- Cluster background turbulence:
  - inner: $v_{1\sigma} \sim 200$ km/s
  - outer: $v_{1\sigma} \sim 300$ km/s
- Jets generate strong turbulence
- Detectable with ASTRO-H, Athena

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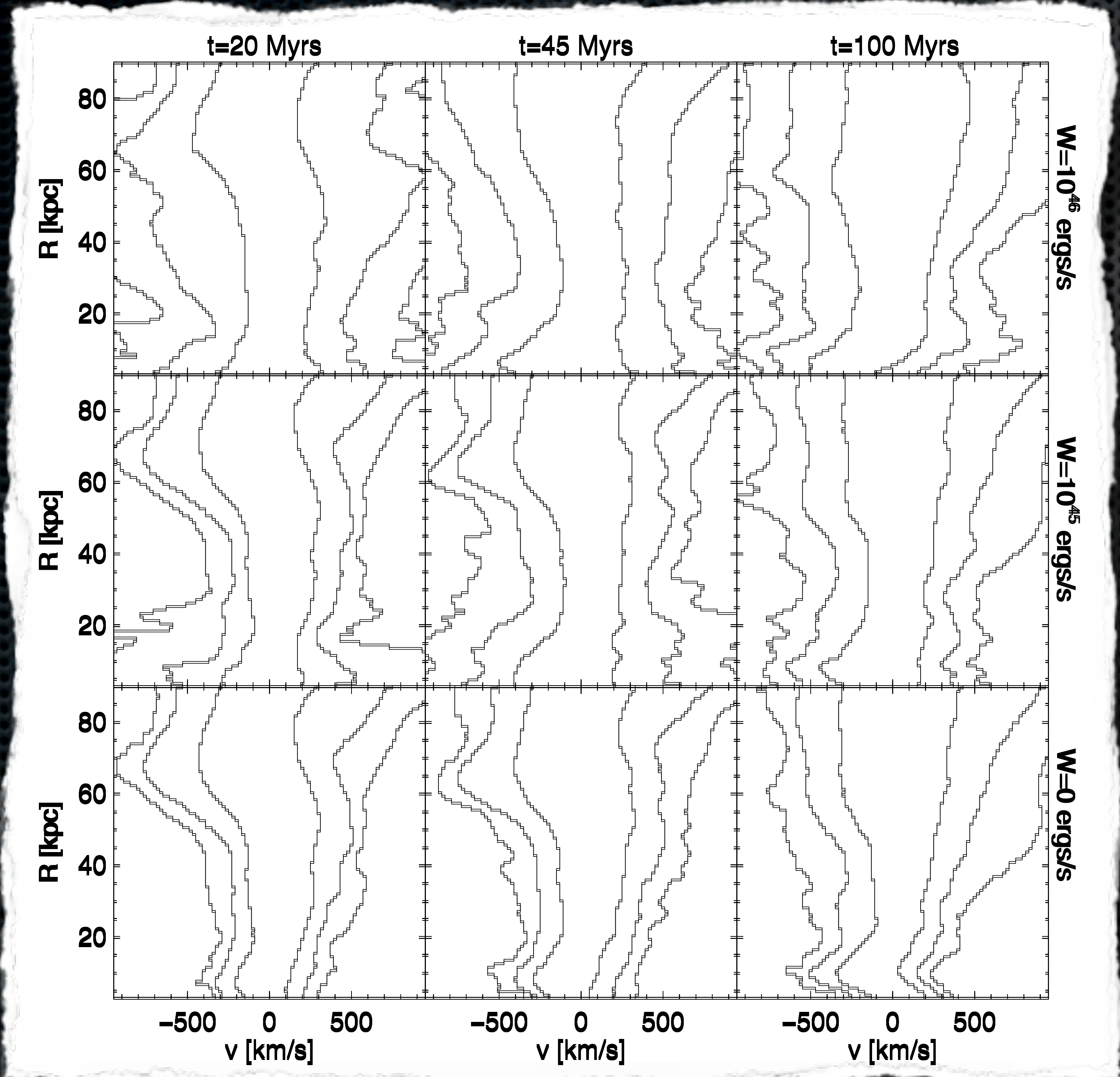

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Summary

- Cluster cavity observations reveal as much about the properties of jets as they do about clusters
- Dynamical properties of clusters are important for radio source evolution
- Multiple cavities ≠ intermittency
- Sphere of influence of Jet on cluster limited by dynamics, with $R \sim P^{1/3}$
- High resolution X-ray spectroscopy has great potential for studying feedback